NASA Contractor Report 3131

Development of Assembly and Joint Concepts for Erectable Space Structures

G. G. Jacquemin, R. M. Bluck,
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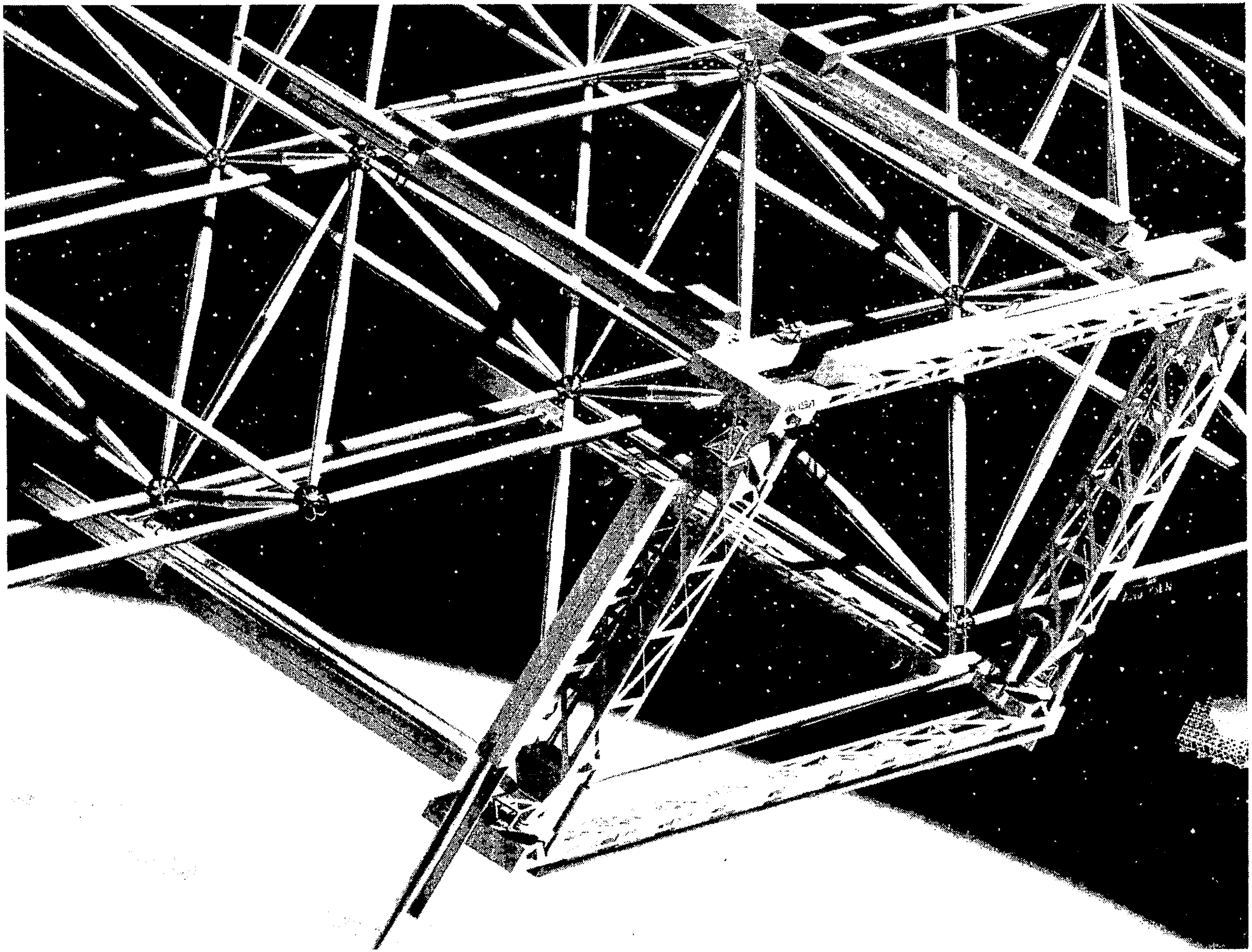

LARGE SPACE PLATFORM AUTOMATIC ASSEMBLY MACHINE

NASA Contractor Report 3131

Development of Assembly and Joint Concepts for Erectable Space Structures

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Section 1
SUMMARY

Several concepts of assembly were investigated during the study. The gimballed parallelogram assembler, orbit-attached or free flyer, has evolved as the primary concept. For the free flyer, columns and node joints are off-loaded from the Orbiter. Other concepts that were considered are included in this report because significant technology associated with assembly was developed during these studies. Additionally, these alternate concepts help to establish trade-off data.

Two different types of nine-member node joints applicable to the on-orbit assembly of tetrahedral truss platforms were designed and manufactured. Two automatic assembly machines, using the two node concepts, were investigated. One of the machines is based on a moving parallelogram type structure. The other is a tracked system. Estimates were made on the time needed to assemble tetrahedral truss structures of up to 1 km^2 in size. The automated assembly systems have the potential of reducing the time of erecting a 1 km^2 platform to less than 20 days, if columns can be transported rapidly. The most significant parameter in determining the assembly time for large platforms was found to be the Space Shuttle turn-around time.

The gimballed parallelogram assembly machine results in a fully automatic concept requiring only a single flight of the Orbiter for delivery of columns and node joints for on-orbit erection of a tetrahedral space platform. Approximately 36 hours are required for this high speed system to assemble all the 20 m columns that can be delivered in one flight.

The need for Extra-Vehicular Activity (EVA) support is discussed, with the primary function being to assist in the unloading of the node joints and column canisters from the Orbiter, and in monitoring, directing, and trouble shooting the automatic assembly process. The joint concepts considered have astronaut assembly as a contingency mode of operation.

A number of technology areas associated with the erection of truss structures using an automated system were studied. These included:

- Design of a center-hinged folded column
- Methods for mechanically assembling half-columns
- Packaging of joints and columns in the cargo bay
- Considerations affecting the continual on-orbit operation of mechanisms
- Selection of energy sources.

Section 2

INTRODUCTION

Large space platforms employing nestable columns have been proposed for a number of applications, such as communication satellites, multi-kilowatt power modules, and space manufacturing facilities. Several industry and NASA investigations have characterized these platforms as tetrahedral truss structures erected from graphite/epoxy columns. The feasibility of erecting these structures on-orbit depends on the design and development of operational concepts for assembling the basic structural elements into the required configuration.

A key feature of these trusses is the nine-point node or cluster joint. This joint must be designed to be compatible with the truss assembly method. This report describes two such joint concepts, which are designed to be compatible with the automated assembly system, and to exhibit an EVA assembly capability.

The guidelines defined for this study are listed below, and will be further discussed later in the report:

- The basic truss elements are the Langley Research Center graphite epoxy nestable columns. The baseline column length is 20 m.

- A column load of $\pm$ 4,448 N (1,000 lb) is assumed for joint design purposes.

- The joint designs are applicable to the assembly of a tetrahedral truss which has nine columns terminating at one truss node. All node joints in the structure are identical.

- The joint designs result in zero free play around or along any column axis.

- The joints are designed so that any column can be removed and/or installed between any two adjacent nodes which are rigidly fixed.

- The truss joint components affixed to the column ends are identical and do not interfere with the nesting features of the columns.

- The primary erection mode utilizes automation as much as possible during the assembly process.

- Hard points are provided at the nodes for erection purposes and the attachment of mission equipment.

- The baseline structure to be erected has an area of 1 km^2.

- EVA backup mode is provided.

Performance on the contract was under the management of H. Cohan. R. R. Johnson was the Project Leader.

Use of trade names or names of manufacturers in this report does not constitute an official endorsement of such products or manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

Section 3

TETRAHEDRAL TRUSS STRUCTURE

The typical tetrahedral truss acts as a space platform. Mounted to the structure will be solar arrays, reflectors, astronaut habitats, and supporting equipment. This truss is erected from tapered graphite epoxy half-columns which are snapped together at the larger ends to form full columns. The half-columns and the node joints required to attach the columns together are transported to Low Earth Orbit (LEO) by the Shuttle Transportation System (STS). Depending on the specific mission of the platform, the size of the columns will vary. This study addresses the assembly of platforms up to 1 km^2 using 10 m long half-columns which taper from 25 cm to 5 cm diameter. The number of columns required for a 1 km^2 structure is 25,981 - 20 m long (51,962 - 10 m half columns), as reported by Mikulas et alia (Ref. 1).

Except along the platform boundary, nine columns are joined at each node. There are approximately 5,774 nine-member nodes required for the 1 km^2 structure. In order to efficiently assemble such a structure, an assembly system requiring a minimum amount of time, and node joints compatible with the assembly system must be developed.

Two node joint concepts are discussed below which are compatible with the assembly systems described in Section 5.1 and Appendix A.

Column Geometry

Two basic column lengths have been considered in this study:

1. For the construction of small platforms, a nominal 5 m column is used.
2. For large platforms, a 20 m column is a practical maximum which is related to the allowable stowage length in the Space Shuttle cargo bay for stacking of half-columns.

Typical column geometries are shown on Fig. 1 and half-columns on Fig. 2. The nominal column lengths are quoted from the centerlines of the node joints, therefore the actual length of the columns is somewhat less than the given value and depends on the connector configuration. Two half-columns, connected by the large ends, constitute a standard column.

These half-columns in their present configuration, are fabricated as a thin wall tapered shell made of graphite epoxy with bonded aluminum fittings at each end. The shell thickness is of the order of 0.80 mm (about 0.025 in.). This design allows stowage by nesting, which permits, in the case of the 20 m column, storing in excess of 50 half-columns within the length of the Space Shuttle cargo bay. In the case of the 5 m columns, the maximum stacking length is better defined from the assembler practical canister length which may be approximately one third that of the 20 m column.

Since the column spacing in the stacks remains approximately the same for all column lengths, it is evident that the longer columns have a significant stowage advantage over the shorter models. This consideration is good justification for the selection of the 20 m column as a design baseline, while the 5 m column remains a practical, experimental size.

Typical Platform Frame

Typical arrangement of an assembled space frame is shown on Fig. 3. The dimensions given are based on 20 m column lengths. A similar platform built from 5 m columns would have the following dimensions:

Column Length (m)	Height (m)	Triangle (m)		Side View (m)
20	16.33	17.321	11.547	10
5	4.08	4.33	2.887	2.5

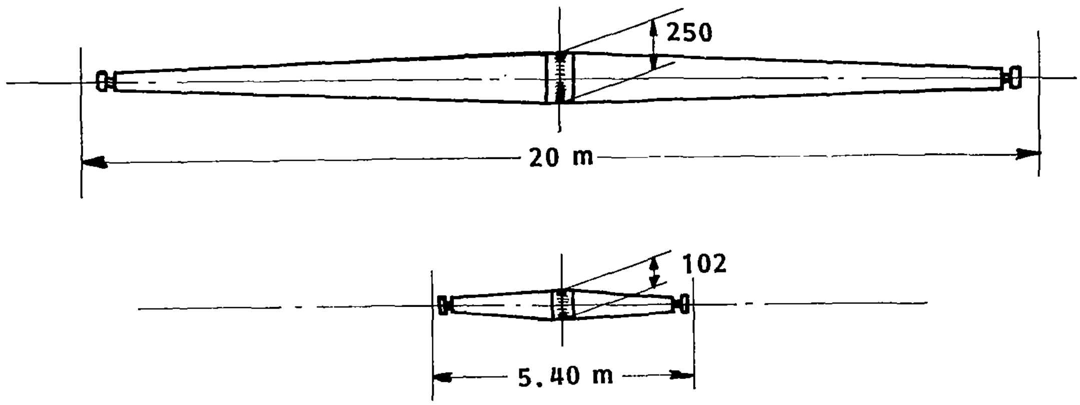


Figure 1. Typical Column Geometry.

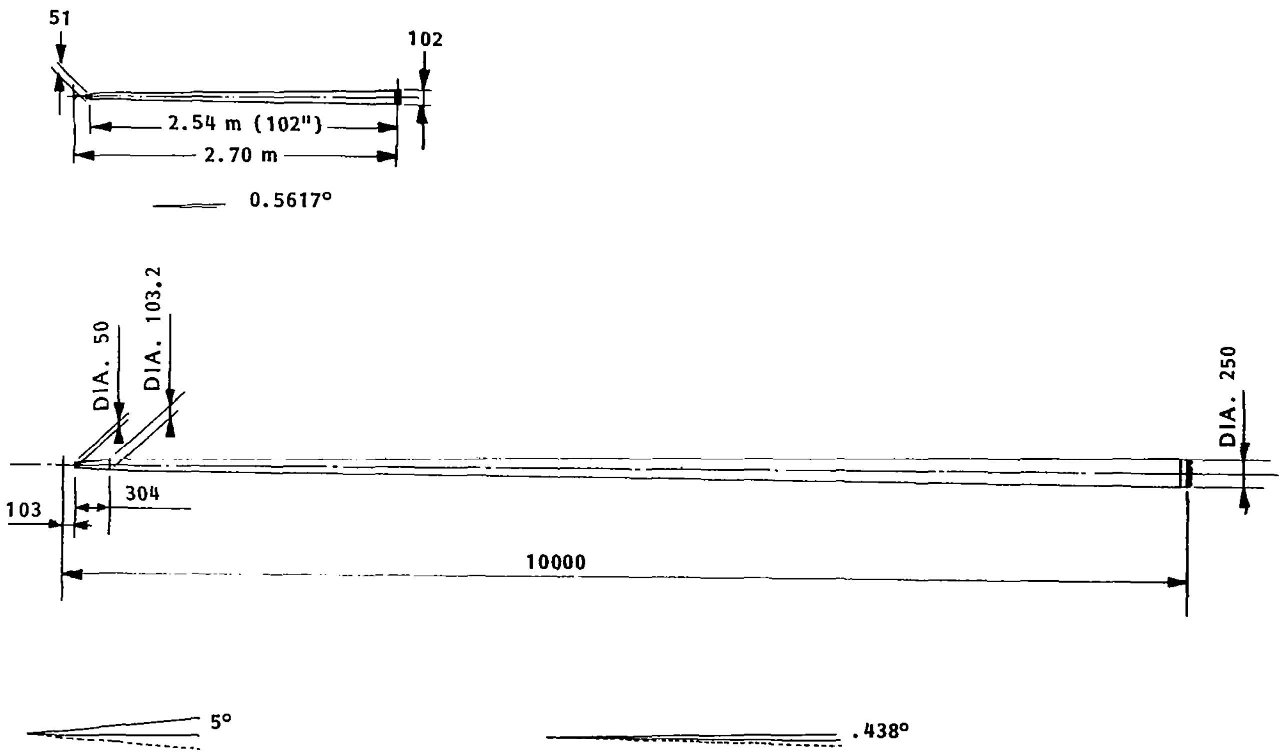


Figure 2. Typical Half-Column Geometry.

Platform planforms which may be constructed with the tetrahedral structure include equilateral triangles, hexagons, rectangles as shown on Fig. 3, beam-like structures of two column widths or more, and various shapes such as Vs and Ls. In addition, beam-like structures can be built with 60 deg angles, making it possible to construct hexagonal toroid planforms. However, closure of the loop would most likely require manual installation of the last few columns.

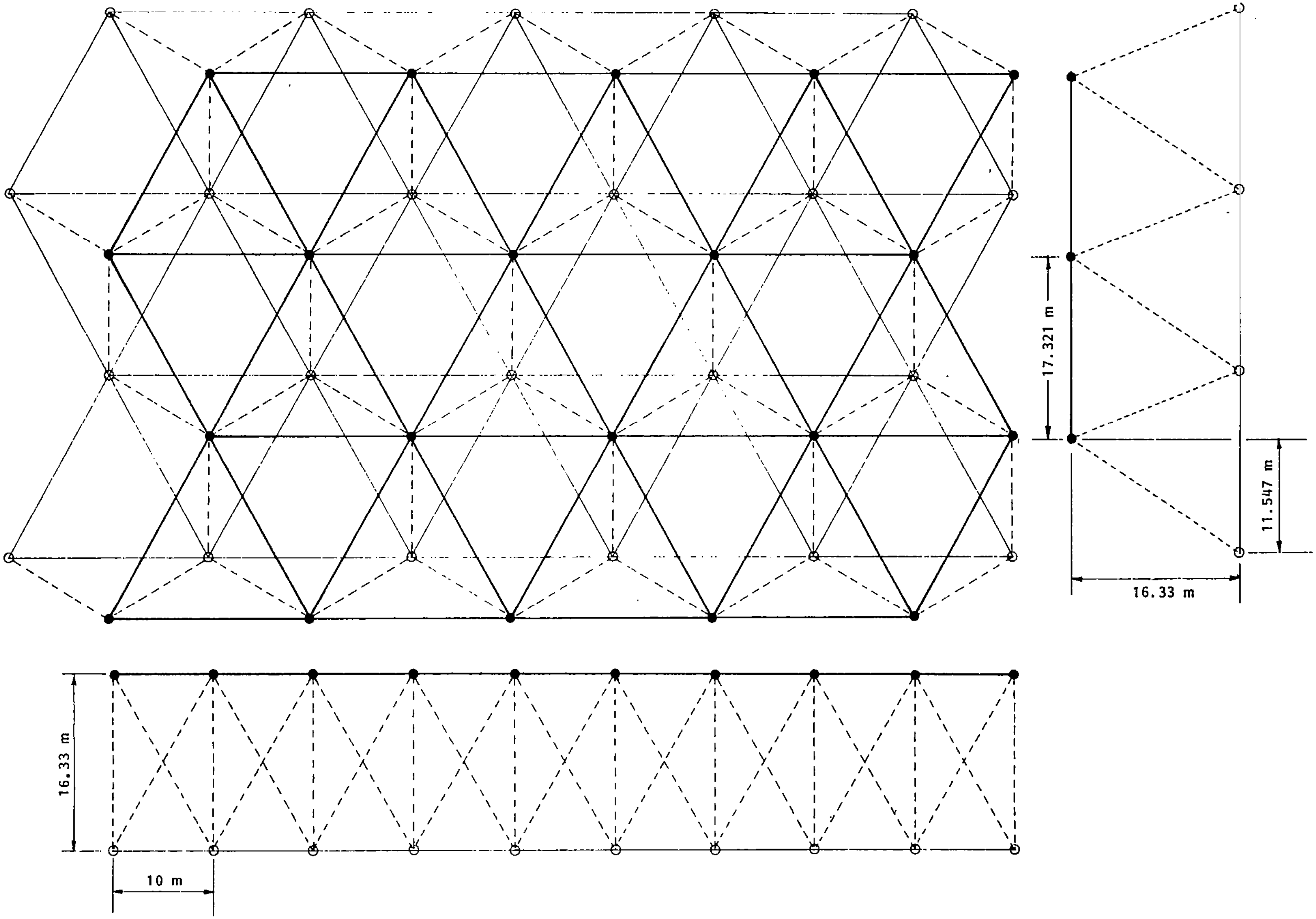


Figure 3. Space Platform; Plan, End, and Side Views.

Section 4
TRUSS JOINTS

The two truss joint concepts selected for evaluation and fabrication are described in this section. These joints are designed to be installed using the automatic assemblers described in Section 5. In addition, the joints are compatible with manual assembly, and release mechanisms or tools are provided for removal of individual columns.

All node joints in the truss are assumed to be identical. Acceptance of this assumption leads to two types of joints and their associated complexity. If entry (or exit) to the joint is directional, the insertion of the ends of the core columns will be from opposite directions between two fixed nodes in the upper and lower faces of the truss. If no entry directionality is built into the connector, the columns may be inserted directly. In the case of the former concept (directional), stops are easily designed into the joint/connector. In the non-directional concept, the stops must be built into the assembly system. The advantages and disadvantages of both systems will become more apparent when the assembly concepts are described in Section 5.

One joint of each of the two types was selected for design and fabrication. The "snap lock" design requires directional insertion, and the "finger lock" is non-directional.

4.1 SNAP LOCK DESIGN

The general principle of the system is shown on Fig. 4 and 5. It is designed for lateral entry, since axial plugging is not possible in these structures without introducing a complex system of sliding components.

The components of the connectors mounted at the ends of the 20 meter column are shown on Fig. 4. Essentially, the components consist of a bolt having a special head which is hollowed out for weight saving, and locked in place by a jam nut, which can be wire locked (or otherwise) once ground adjustment has been performed.

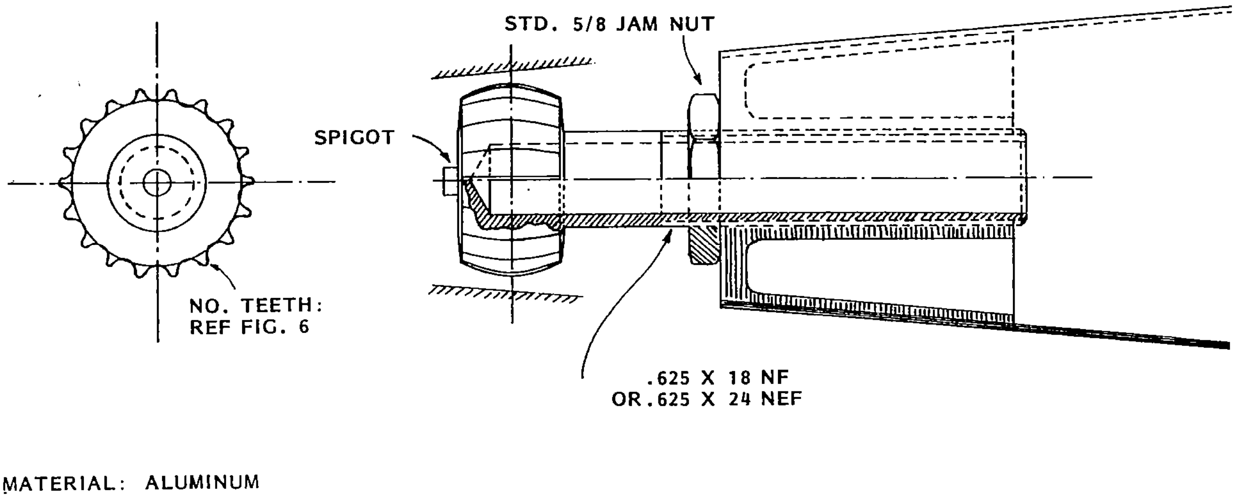


Figure 4. Automatic Connector, Typical Column End Fitting.

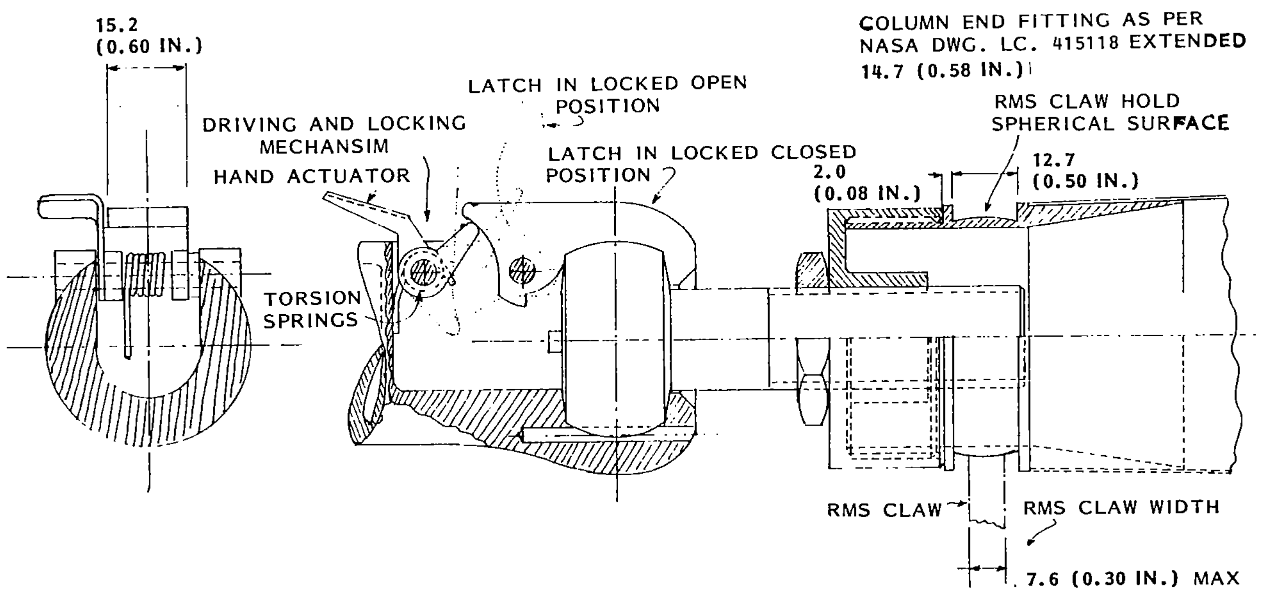


Figure 5. Details of Snap Lock Column End Connector and Node Mechanism.

The sprocket-like teeth on the bolt head are designed to fit over the pin shown on Fig. 5, thereby locking the column against torsion. The circular faces of the bolt head are 80 degree cones designed to lock into the matching housing receptacle, in order to provide bending fixity of the joint. The front spigot is designed to catch the cam of the latch.

During the assembly sequence, the special bolt head is guided into the proper place by the special funnel shape of the housing, as shown on Fig. 5. This ensures that the alignment of the column need not be critical and that its spigots will not miss the cam of the latch as it penetrates into the receptacle.

The mechanism shown on Fig. 5 is based on a cam system designed to provide a large mechanical advantage to the torque of a fairly small torsion spring. Tests with the fabricated joint show that insertion can be performed with minimum effort and the joint offers good rigidity in the locked configuration without requiring external application of preload.

The general principle is as follows, with reference to Fig. 5:

> The aft end of the latch (left, on Fig. 5) is designed to provide two cam surfaces. One cam surface is designed to secure the latch in the open position. Upon passing a top dead center (t.d.c.) point, the lock drives the latch over to capture the end connector ball. The locking finger then swings along the second cam surface, which is designed as a ramp, against which the locking finger jams itself, thereby securing the connector ball under a preload.

Connector Release

If it is necessary to remove a column, the connectors can be disassembled by using the hand actuator, and swinging the latch to a partially open position to let the spigot rise over the cam. The strut end can then be tapped out of the housing and removed while the latch is swung to its fully open position.

For this operation to be performed in orbit, a tool can be devised to require only a single motion of the operator. It is assumed that replacement of a column will be performed via EVA.

General Dimensions of the Mechanism

The dimensions of the mechanisms were selected to be as compact as possible to save weight and cargo space on the Space Shuttle. Another criterion which must be satisfied is the requirement of stacking the half columns for stowage in loading magazines. This led to a 38-mm (1-1/2 inch) connector diameter.

Relative Positions of End Connectors with Center Joint Coupling

A definite relationship must exist between the angular positions of the half column end connectors and center joint coupling in order to ensure that the two end connectors are properly oriented to match their respective torsion locking pins. This relationship is shown on Fig. 6 for a typical 24 prong center coupling. The number of teeth on the end connector must be equal to the total number of prongs of the center connector; i.e., twice the number of prongs of the half connector. The relative setting of these two connectors, as shown on Fig. 6, can be easily guaranteed on an appropriate assembly jig also designed to adjust the half strut length within specified tolerances.

Note that the relative positioning of these two connectors imposes a step increment to the half strut length. For a 24 position system, as shown on Fig. 6, and an 18 NF screw, this increment is 0.058 mm (0.0023 in.) per step; well within practical tolerances on a 10 m half-column.

Nine-Connector Node

Figures 7 and 8 present the application of this concept to a nine-connector node, designed to be as compact as possible in order to reduce offsets to a minimum. This layout fits within a circle of only 182.9 mm (7.20 in.) diameter. The six in-plane connectors all have their latches on the outside face

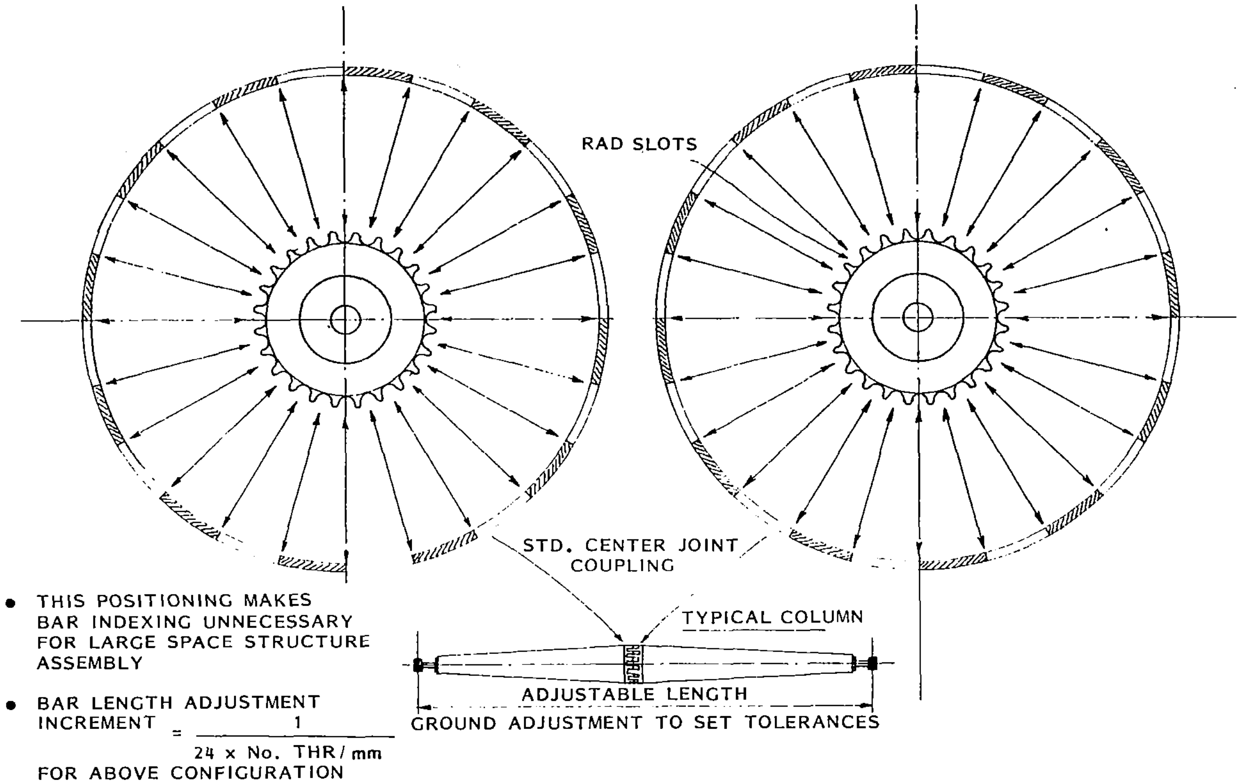
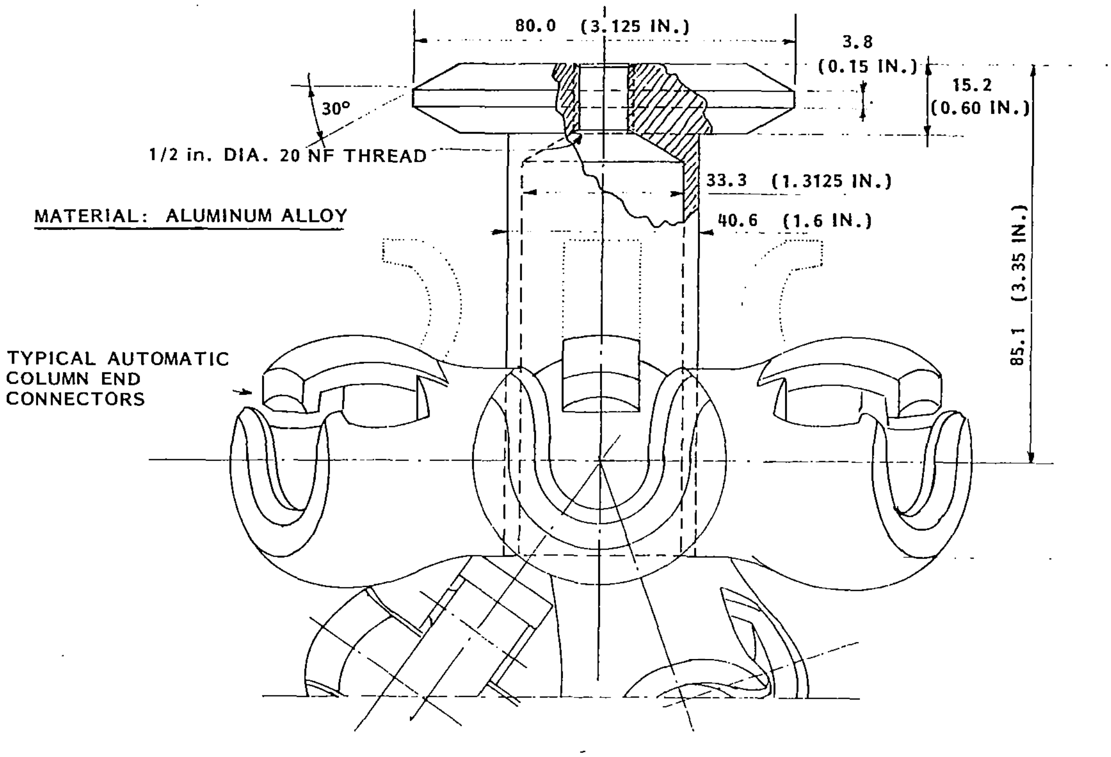


Figure 6. Automatic Column Connector, Relative Positions.

of the node, thereby giving easy access to the coupling housings. The three off-plane connectors shown on Fig. 7 are inserted laterally to prevent interference with each other. Figure 7 presents a side view of the node with the outline of an additional connector which may be used for payload attachment and for handling at assembly.

Material and Fabrication

As shown, the connectors are machined from aluminum bars and welded together to form the nodes. This is acceptable on an experimental basis only. For production, the housings could be made from aluminum castings if the loading conditions permit, or alternately, forgings. In either case, machining of only the internal cavities would be required.



Dimensions are given in mm (in.)

Figure 7. Compatible Node Holder.

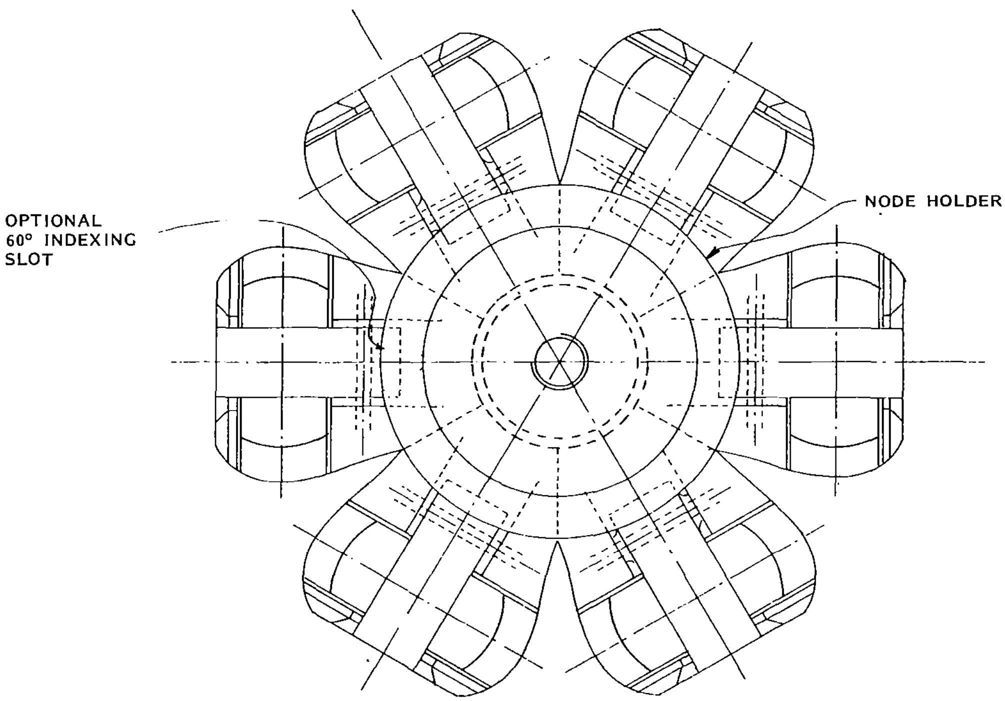


Figure 8. Compatible Node Holder (Top View).

Figures 9 and 10 show the manufactured node joint. The joint cluster weighs 1.701 kg and each of the columns end connection balls with screw shank weighs 145.15 g, or a total of 1.306 kg for the nine connectors.

4.2 FINGER TYPE NODE JOINT CONNECTOR

Purpose and Operating Principle

The function of this node joint connector is similar to that of the snap lock design described in Section 4.1. This system was selected because it results in a compressive joint preload, in addition to not imposing any directional constraints on insertion of the columns between two node joints. This mechanism, however, does require alignment stops and a secondary motion to lock. EVA compatible tools are needed in case of removal from and replacement of a column into an existing structure.

The operating principle is similar to that of the column connector described in Appendix B. It consists of a set of grasping hooks at the end of aluminum flexure springs machined out from a sliding collar. After alignment of the column with the node joint is achieved, the sliding collar is pushed over the node joint barrel until the hooks snap over a locking edge. Finally, in order to secure the mechanism, a locking ring is automatically pushed over the hooks by a spring, to prevent all possibilities of disengagement.

Description of Node Joint and Mechanism

This device consists of one passive element and nine active connectors. The connectors are fitted at both ends of each column. The passive element is the node joint itself, which is shown on Fig. 11. It consists of nine identical half-connectors, fitted and welded into a center body which incorporates a special mushroom head designed for grasping by the platform assembler node retainer system. This node joint has no moving parts, but each bucket-like half-connector includes a grasping ring designed to provide a hold for the assembly end-effector mechanism.

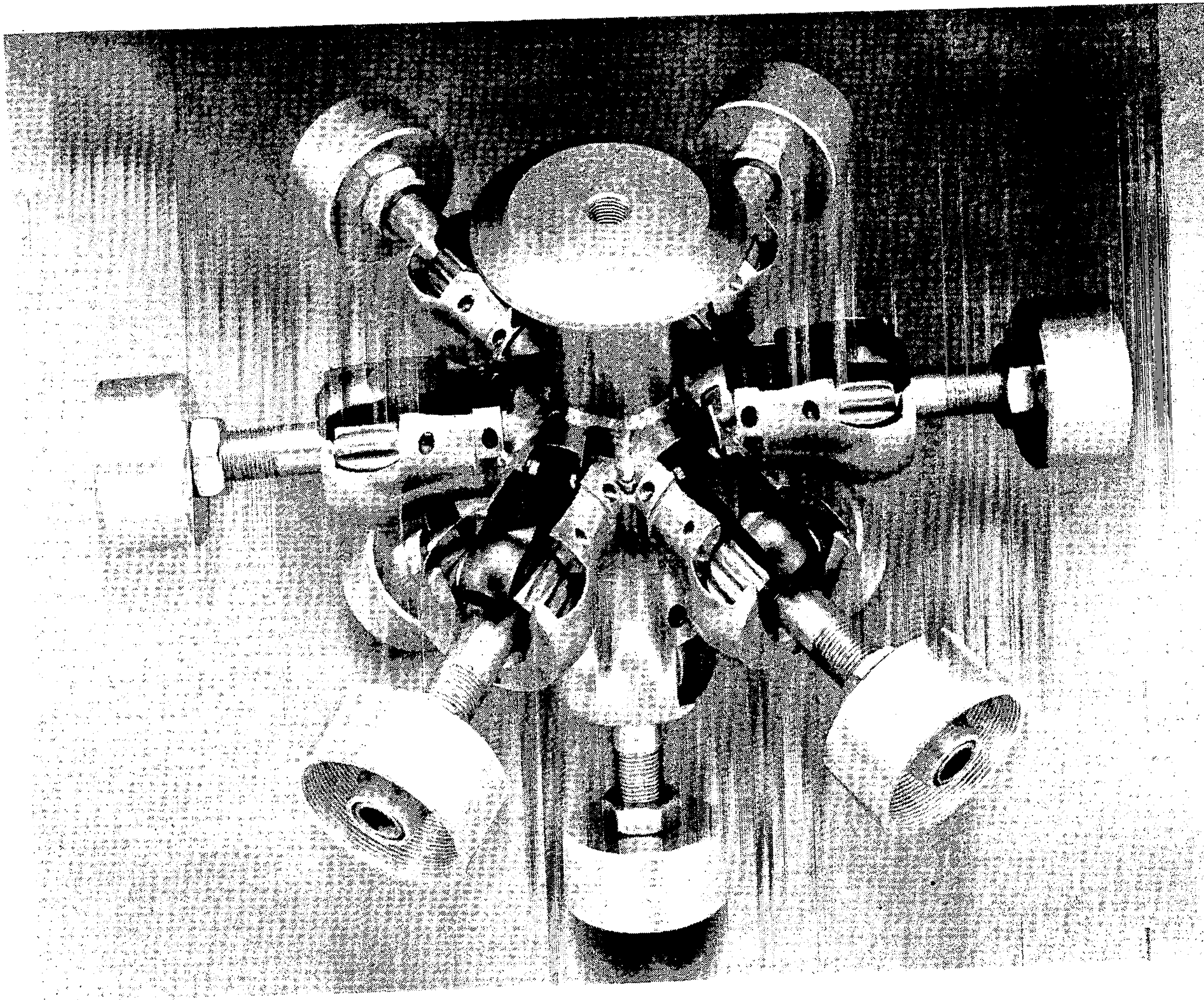


Figure 9. Snap Lock Node Joint.

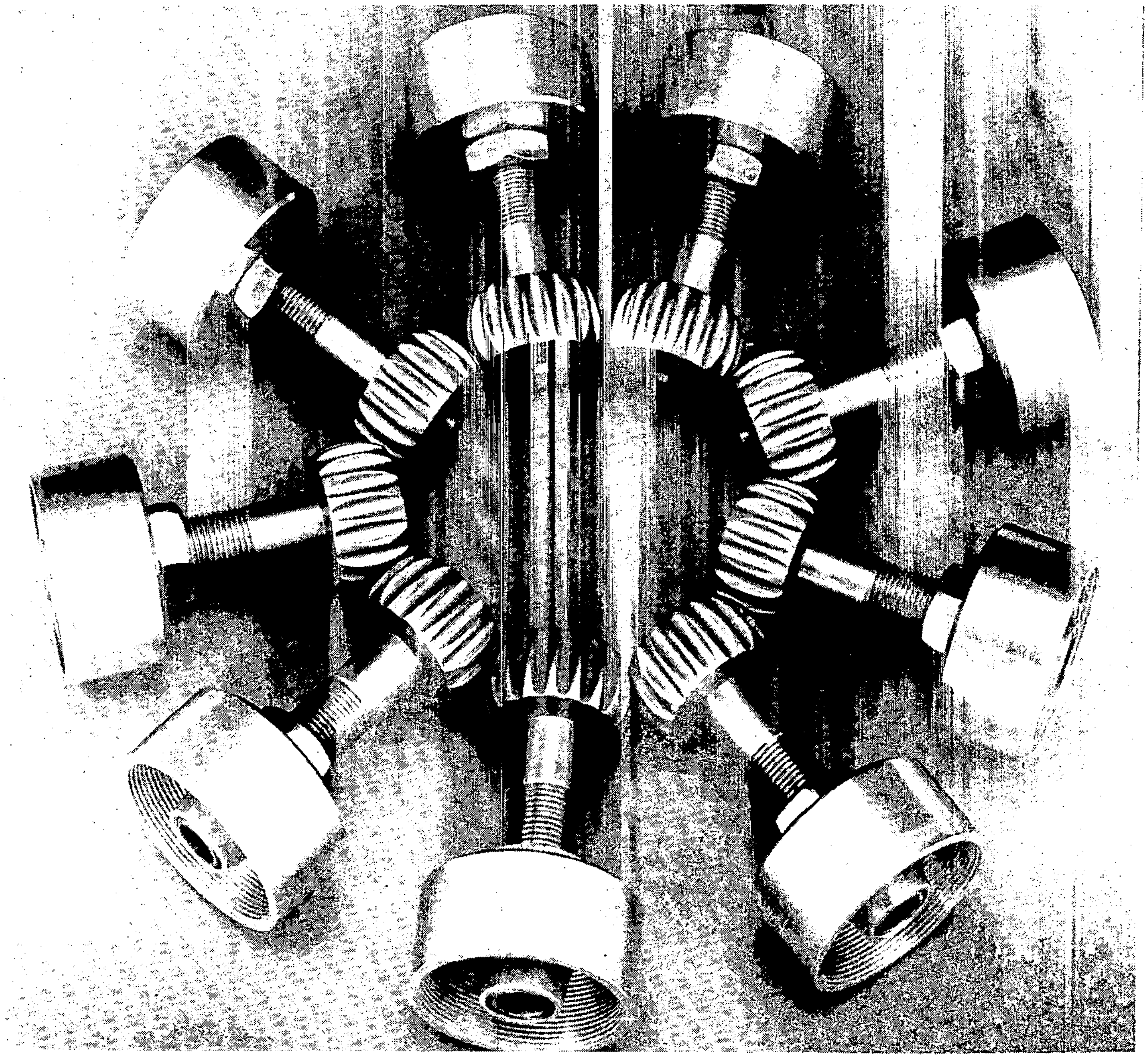


Figure 10. Snap Lock Node Joint (Column End).

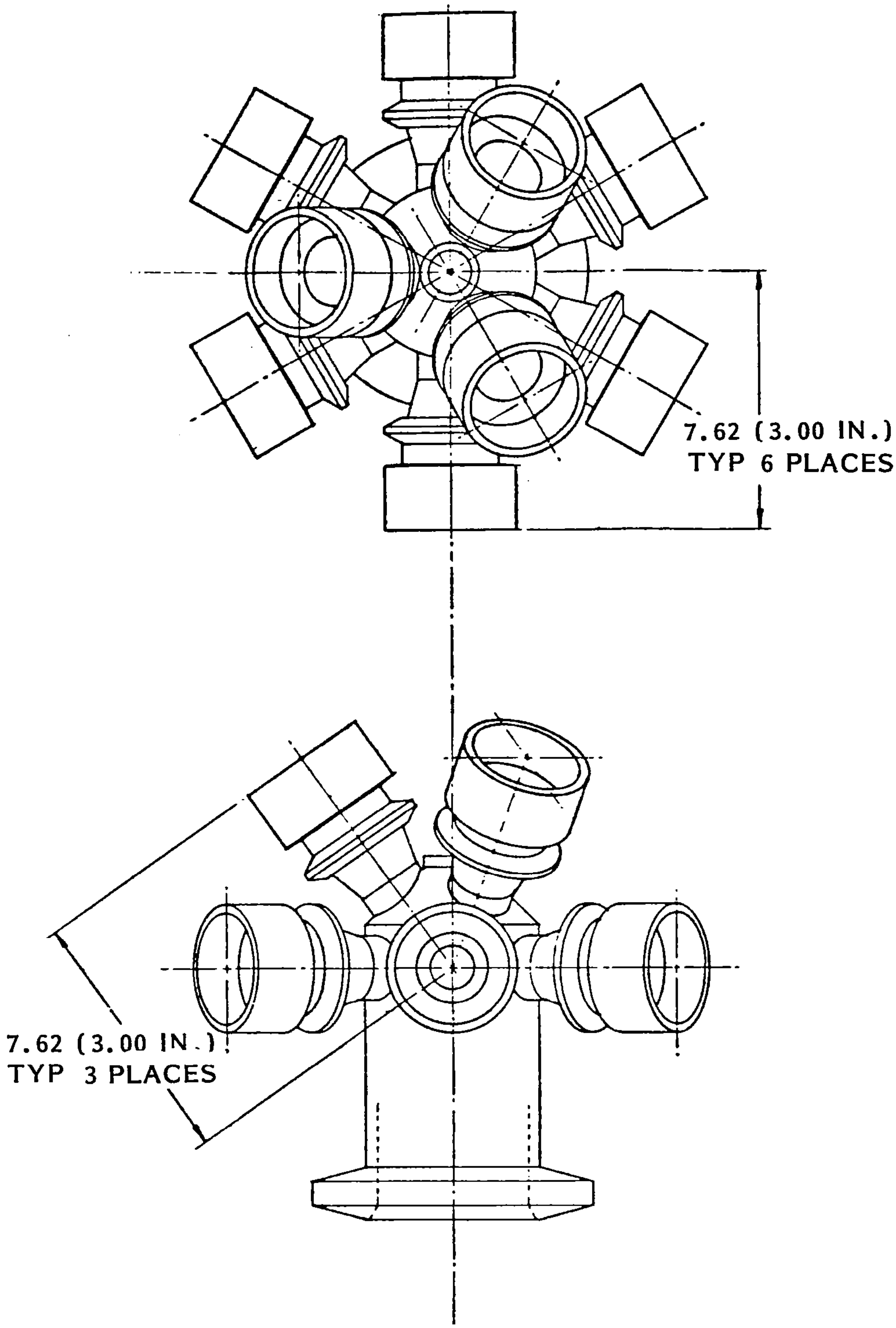


Figure 11. Finger Lock Connector, Nine-Column Node Joint.

The active connector is described on Fig. 12, where the system is shown locked, and the detail sketch in the pre-lockup position. The operation of this mechanism is described with reference to points A and B and positions C_1, C_2, D_1, and D_2 on Fig. 12. A mechanism is necessary to provide the axial translation required to operate this connector.

The sequence of operations required to align and lock up one of these column connectors is as follows:

a. The column is held at point A by a holding device on the column inserter.

b. The column is inserted between two node joints.

c. The column inserter guides the column end until a second holding device takes hold of point B. This guarantees proper alignment of the column and node joint.

d. When both ends of the column have been presented to their respective node joints (to prevent any offset), a specified compression force is applied by the insertion mechanism between points A and B to assure closure.

e. The insertion mechanism is then required to push the sliding ring from position C_1 to position C_2 and applies a compression load in the direction of point B to ensure that all grasping hooks snap into locked position.

f. As soon as the grasping hooks snap shut, the safety collar is free to move from point D_1 under the force of the spring and jam itself against the hook conical ramp at point D_2, thereby securing the system. If it is found necessary to lock the claws under a higher

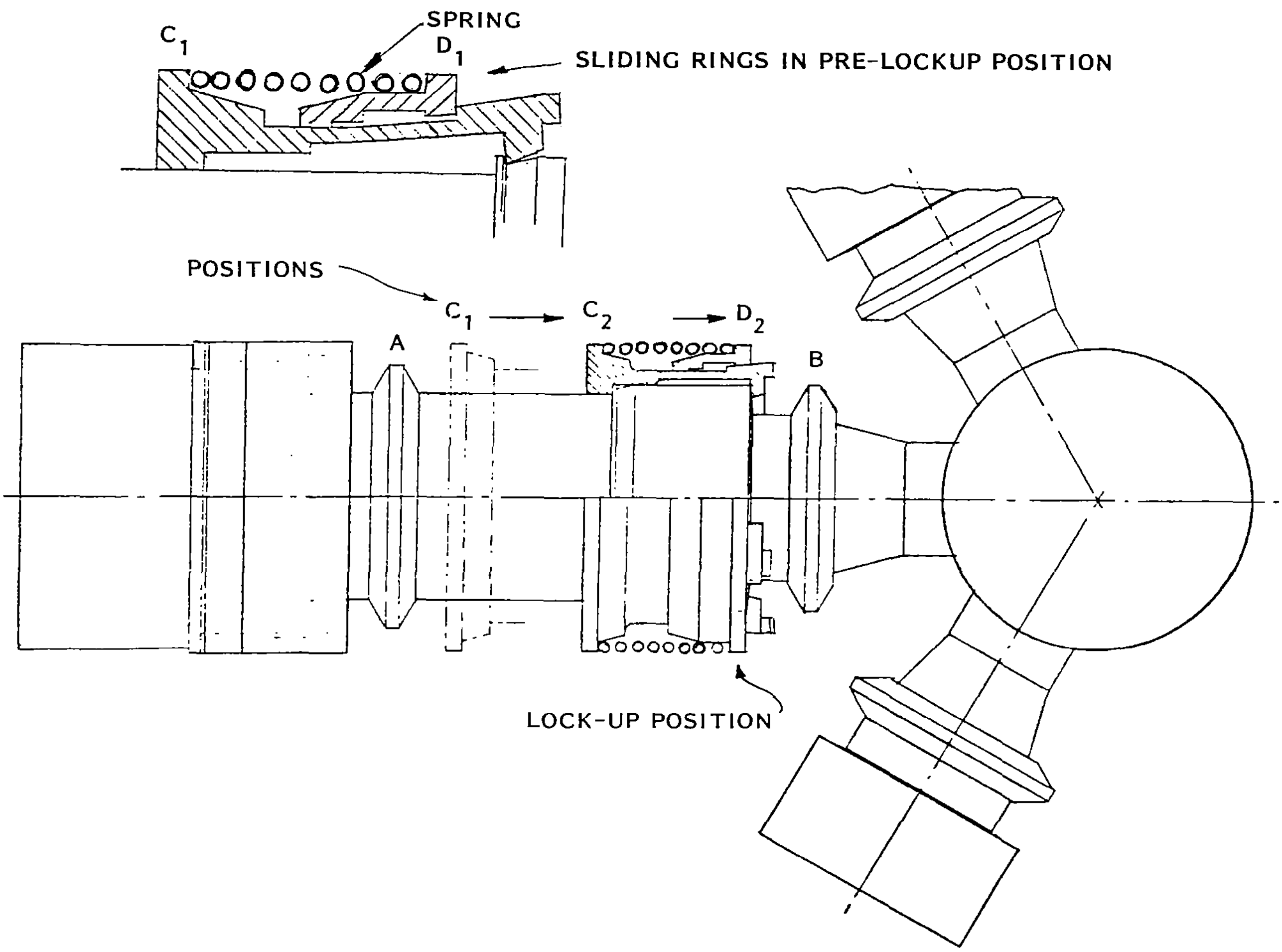


Figure 12. Details of Finger Lock Connector Mechanism.

pressure than the spring can deliver, a mechanism can be incorporated in the end-effector to assist in pushing the ring over the cone and locking it under a specified force. In all cases, the spring force will ensure that this collar cannot back up.

g. After lockup is accomplished, the preloads are released in the order C_2 to B and A to B, the holding device opened and the insertion mechanism removed. This completes the assembly cycle.

Description of Finger Slip-Ring and Locking Ring

A finger slip-ring and locking ring are presented on Fig. 13. Both are machined from aluminum alloy.

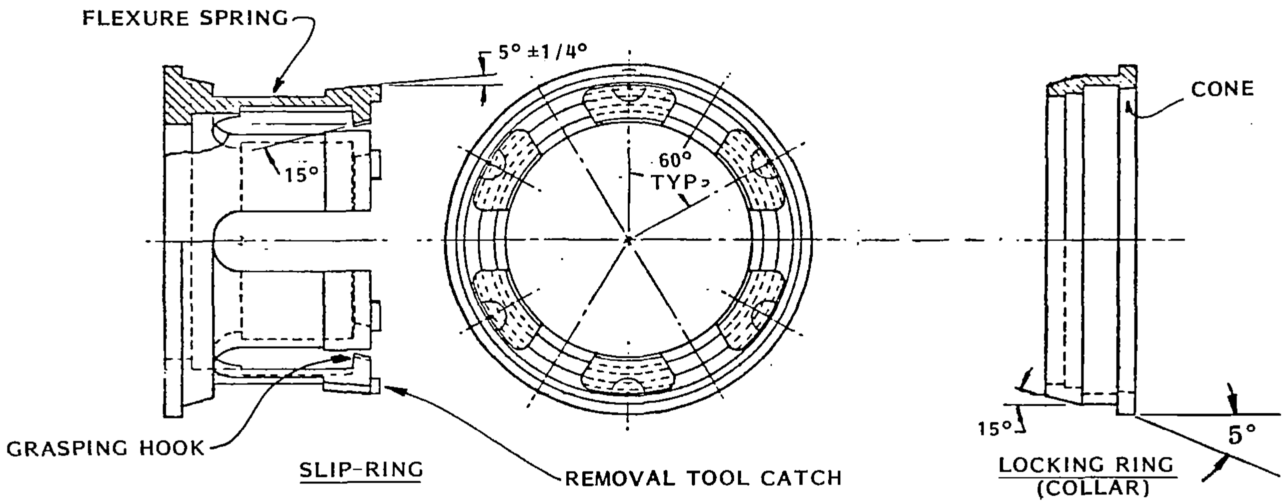


Figure 13. Finger Slip-Ring and Locking Ring.

The slip-ring consists of a stiff collar from which a set of six grasping hooks with their flexure springs are machined. The cross-section of these springs is designed to provide adequate deflection without exceeding 80 percent of their yield stress. Each holding device is equipped with a small semicylindrical extension which is designed for use with a cam type tool, which opens the hooks to precisely the right deflection for assembly and disassembly. The design of the hooks incorporates a 15 degree entry angle to accommodate anticipated alignment tolerances of the end-effector system.

The locking ring (collar) is also shown on Fig. 13. It is a simple part which features an internal cone to match that of the holding devices. If it is found necessary to force this ring into place mechanically by the end-effector, its design can be modified to provide a holding area for the actuator.

Joint Disassembly and Experimental Tool

Disassembly of this joint is performed with special tooling. An experimental tool is available for disassembly in a laboratory environment. This tool is a cam device for opening the grasping hooks. Sliding of the rings is performed manually.

For on-orbit disassembly, a tool suitable for astronaut use would have to be devised. This is not considered to be a significant effort.

Concluding Remarks

Experimentation with a prototype model shows that this connector is capable of providing a tight fit, and resists a significant torque induced by the compressive preload. The wedging features of this connector require that close production tolerances be maintained.

The design of the joint effecting mechanism presents some challenges in achieving the required operations in a compact package since the amount of room for maneuvering a robotic device is somewhat restricted.

The main advantages of this connector are its preload features and independence from the direction of insertion, which is a characteristic disadvantage of other systems.

Figures 14 and 15 show the manufactured joint. A graphite column end is attached to one of the connectors. The joint cluster weighs 726 g, and each of the column end-connectors weighs 181.6 g, for a total of 1.63 kg for the nine-column end-connectors.

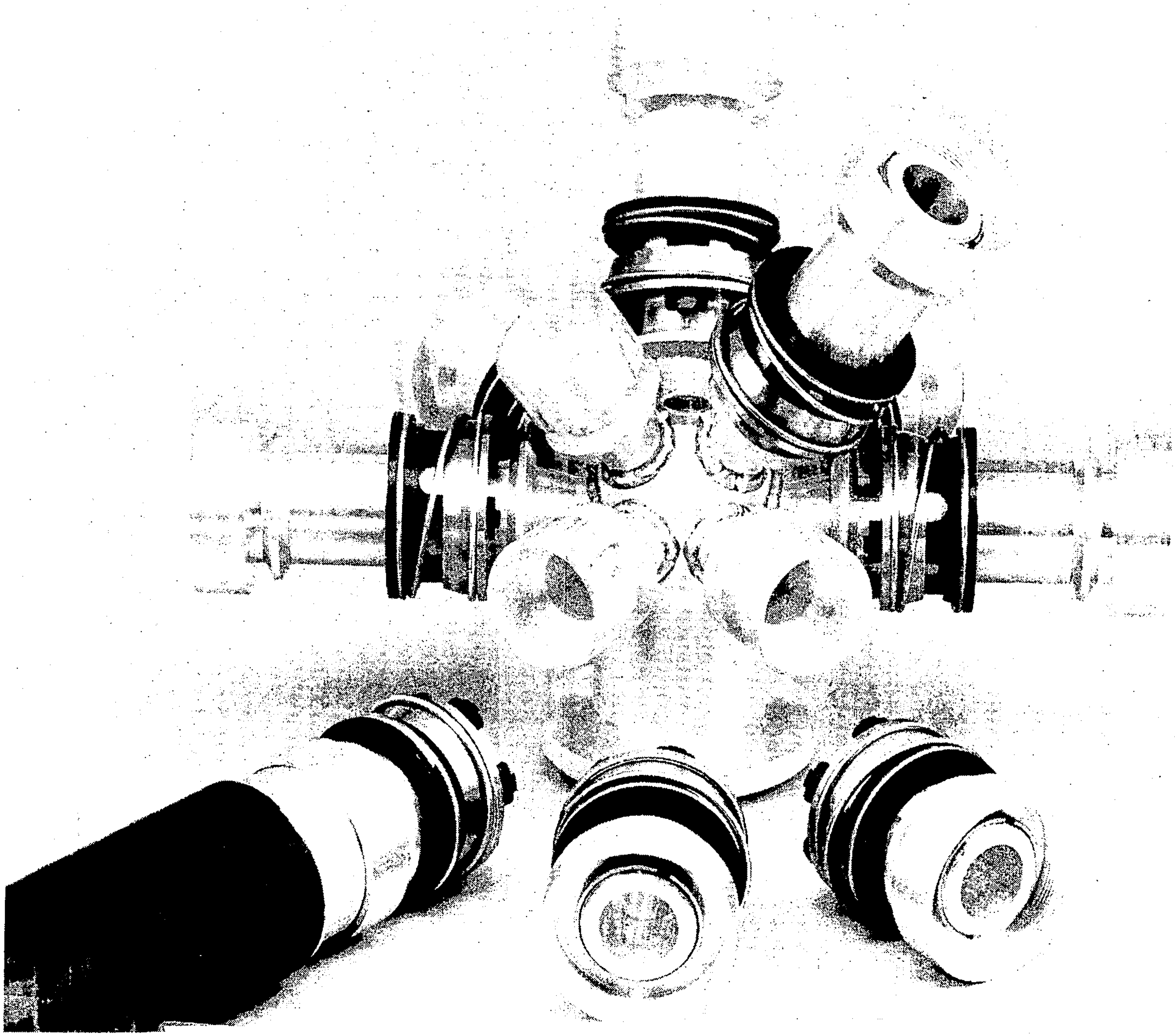


Figure 14. Finger Type Node Joint (Partially Assembled).

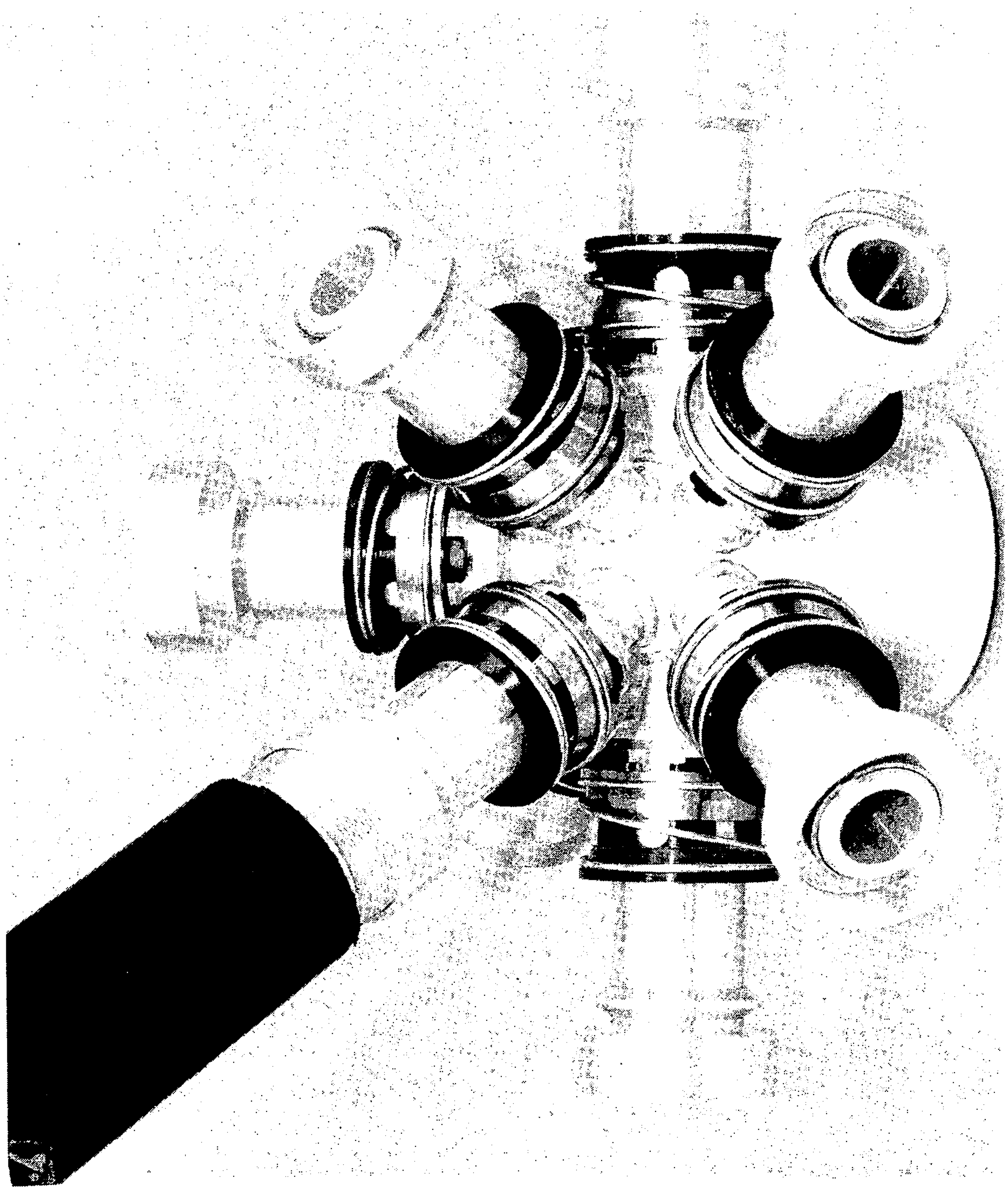


Figure 15. Finger Type Node Joint (Assembled).

Section 5
ASSEMBLY

Several methods of erecting a tetrahedral truss were evaluated and appropriate assembly machines were laid out in sufficient detail to show the principles involved in their operation and to demonstrate the realism of the underlying assumptions. In the course of this investigation three different assembly machines were conceived; two of them are based on parallelogram geometry, one having a rigid base frame and the other being fully gimballed. The third concept is based on a tracked carrier system. In the present state of the study, these assemblers would be built to match particular column sizes and they would be collapsible, preferably in one unit, to fit within the space available in the cargo bay of the Space Shuttle.

The assembly which best fits these requirements is the gimballed parallelogram which is described in this Section. Description of the two other machines have been provided in Appendix A of this report to show the evolution of the concept and a number of mechanisms which are applicable to either solution.

It should be noted also that the present imposition of building the assembly machine to match a unique column size is not an absolute. A number of methods are available to provide some adjustment freedom which would enable the machine to adapt to a range of column sizes. A more advanced study of the machine structure is required to better define the required mechanisms, however a quick look indicates a range such as 15 m to 20 m (or 5 m to 8 m) could be provided. The addition of such a capability has an important side effect; it leads to the consideration of an asymmetric machine using different column lengths to build spherical surface platforms which may simplify the design of very large parabolic reflectors and antennae.

Several assembly options were considered with these assembly machines to establish comparative time lines and evaluate assembly technology. A rigid parallelogram forms the basis for one system, while a fully gimballed parallelogram is that of another scheme, and a continuous, tracked, rigid structure is used in the third scheme. All systems are designed to be fully automatic, with EVA backup and trouble shooting. Two half-column concepts (individually nested and hinged) and two joint concepts (directional access and random access) were evaluated. The following table displays the matrix of concepts considered.

	Rigid Parallelogram	Gimballed * Parallelogram	Tracked Assembler
Column Concept	Hinged/Directional	Directional	Hinged/Directional
Joint Access	Individual/Random	Individual	Individual/Random

* Selected scheme.

5.1 GIMBALLED PARALLELOGRAM ASSEMBLER; DESCRIPTION AND KINEMATICS OF OPERATIONS

The concept of this fixture is shown on Fig. 16 and 17. The node retainers, which have the purpose of gripping the truss at the nodes, are shown in their extended position. They can be retracted during maneuvering of the machine and to secure a node joint from the canisters. A controlling computer may be located within the framework; a crew compartment is optional depending on the size of the platform to be erected and the selected mode of operation. Electrical power may be supplied from solar arrays attached to the machine structure or from a nearby power module by means of an appropriate umbilical.

Definitions

The following terms are defined to prevent misinterpretation.

<u>Traverse</u> - Crab-like lateral displacement of the assembler along the edge of the platform

Right-hand traverse	-	Traverse moving toward the right hand as viewed on the drawing
Left-hand traverse	-	Traverse moving toward the left hand as viewed on the drawing.

5.1.1 Description of Proposed Assembler

The general layout of the assembler is shown on Fig. 16 in a schematic form and in more detail on Fig. 17. The main frame is a quadrilateral, having a gimbal at each corner. The relative position of the members is controlled by a set of eight actuators which are used to align the frame with the structure under construction. A set of four rotating arms completes the machine for the installation of cross members in the two parallel planes. Precision alignment of this machine in any position is controlled by means of a set of laser beams emitted at one reference point, reflected by mirrors and directed toward receivers at strategic locations. Supplies of node joints and half-columns are provided in special canisters. The node joint canisters are located on the rotating arms. The half-column canisters, together with column large-end connection devices are mounted on one side of each member of the machine. The column large-end connection devices extract two half-columns from the canister, select, for each half, the proper orientation and connect the large ends together. The completed column is then transported to a location where robotic manipulators can seize it and insert it into the node joints held by the node retainers.

It should be noted that the only points of contact between the assembly machine and the platform being assembled are the node joints. All motions of the machine are performed from node joint to node joint and, in most maneuvers, only two joints may be unattached. It is only in such maneuvers as change of row or a 60 degree change of direction that four joints may be freed temporarily. This procedure avoids possible unstable relative motions since the assembler maintains a firm grip on the space frame.

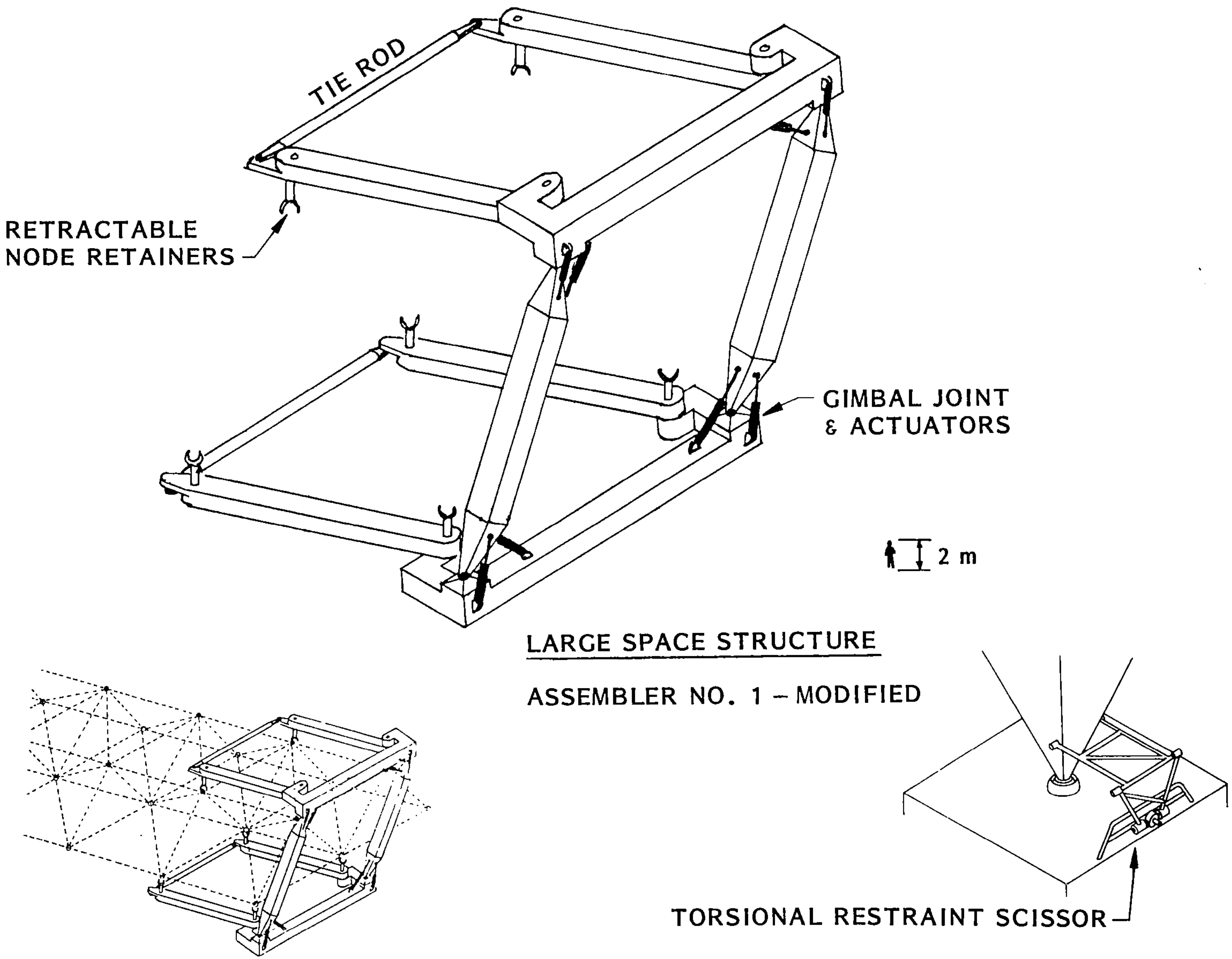


Figure 16. Gimballed Parallelogram Assembler.

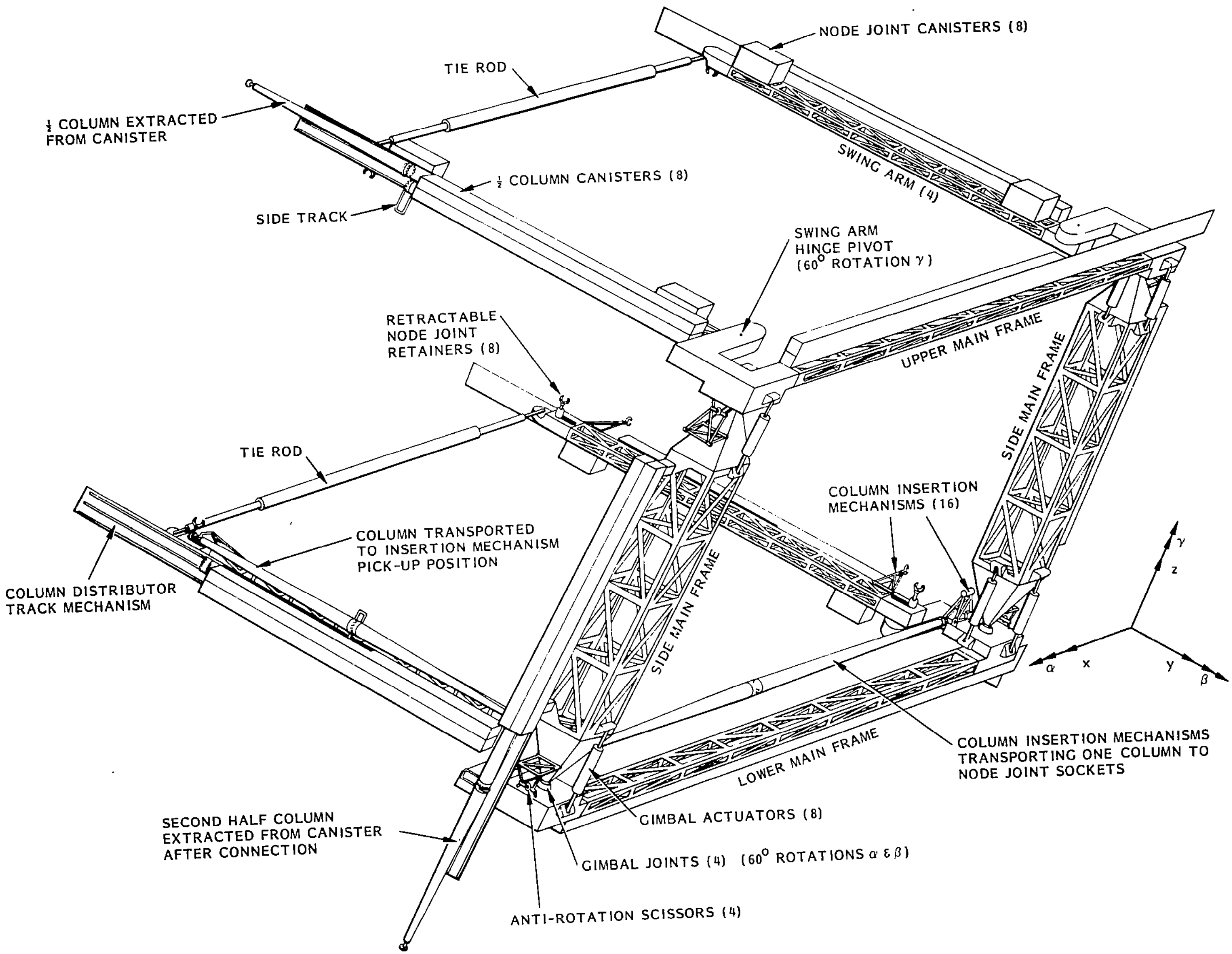


Figure 17. Gimballed Parallelogram Assembler (Detail).

The basic operational concept of this assembler is construction in a free-free mode. However, for small platforms and using short columns (e.g., 5 m) the machine can operate attached to the Space Shuttle in two different modes as shown on Fig. 18 and 19.

Erection of the assembler in orbit can be automated to a large extent by stowing it in a collapsed state in the Space Shuttle cargo bay and using deployment techniques. EVAs will be required for inspection and for installation of specialized equipment.

The main features and objectives of this machine are as follows:

- It will be capable of constructing the first elements of a space frame with minimal EVA assistance.
- It is capable of moving sideways, right, left, or backwards to change rows as the assembly progresses, and to perform changes of direction to any side of the basic equilateral triangle.
- It is capable of constructing large continuous platforms of various shapes such as a triangle, hexagon, rectangle, Ls or Vs, etc. It can also build beams and hexagonal toroids as shown on Fig. 18 and 19.
- All functions are performed electrically (dc or stepper motors) and all working units are easily removable in orbit for replacement and repairs.

5.1.2 Origin of the Concept

The assembler described here is derived in some respects from the two designs presented in Appendix A. The general concept is a refinement and simplification of the rigid parallelogram machine, while the structural details and the mechanisms are taken directly from the tracked assembler. The evolution of these designs provides the following benefits:

- Design simplification
- Reduction of the number of loading points

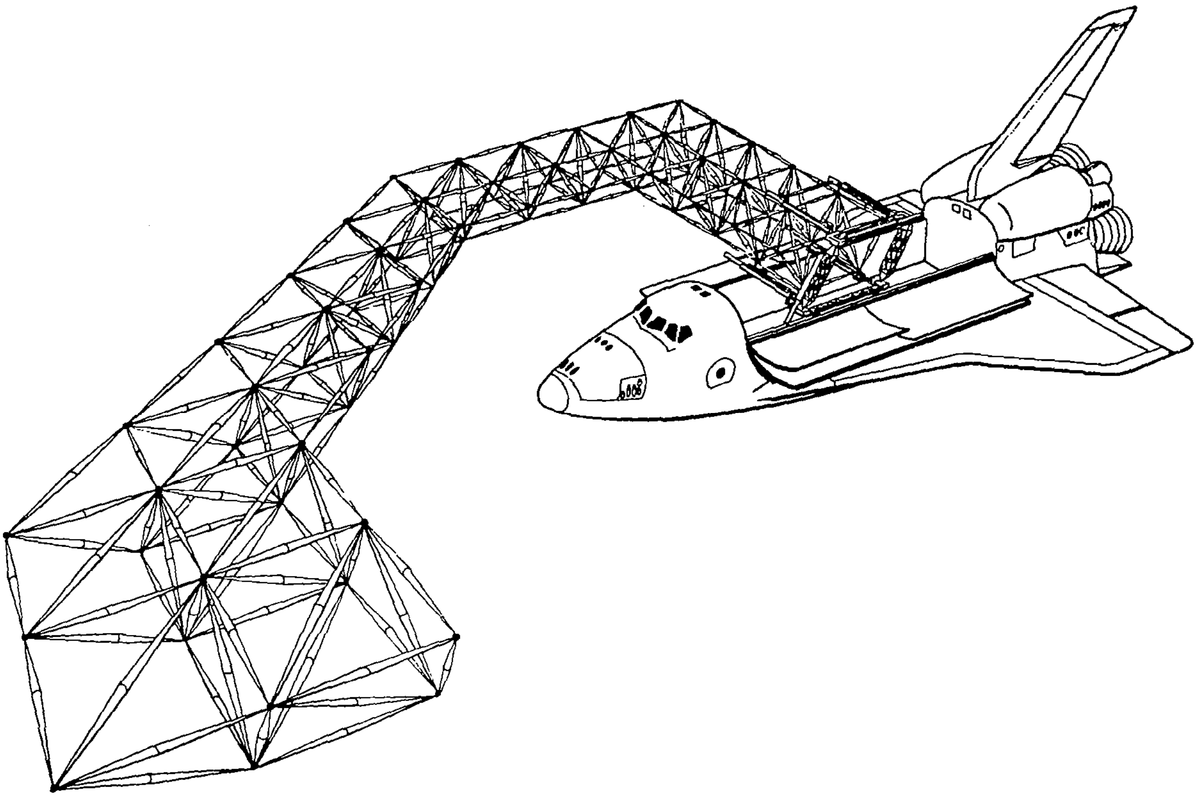


Figure 18. Scaled Down Version of Assembler for 5 m Columns; Installation on Space Shuttle for Fabrication of Linear Structures.

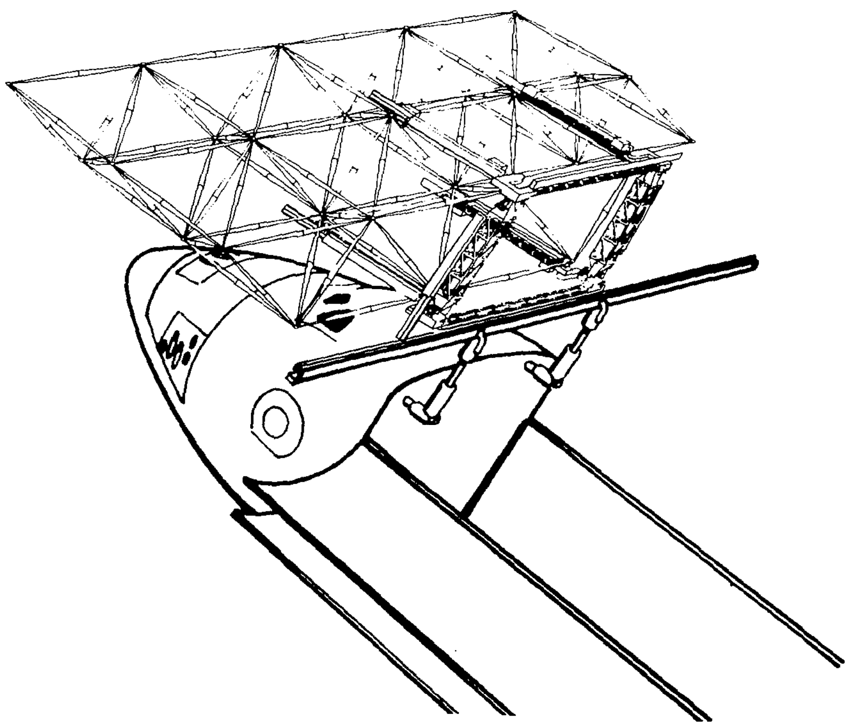


Figure 19. Scaled Down Version of Assembler for 5 m Columns; Installation on Space Shuttle for Fabrication of Small Size Platform.

- Increase in operational flexibility
- Increase in assembly speed
- Improved stowing and automatic erection capabilities
- Added capability of smaller version to work directly from the Space Shuttle.

The features of this assembler and its operation are described in some detail in the following Sections.

5.1.3 Structural Characteristics

The general appearance of the assembler structure is shown on Fig. 17. Each member is an open Warren truss, similar in concept to the layouts generated in Appendix A for the two previous assemblers. The column canisters are all mounted externally to the structure together with the column big-end assembly mechanisms. The node joint canisters are inserted into the beam trusses close to the node retainer systems.

The structure should be made from a material whose sensitivity to thermal expansion matches that of the columns. Therefore, graphite epoxy is a strong candidate, as well as aluminum and magnesium metal matrices. Since these materials have very small coefficients of thermal expansion (negative in the case of graphite epoxy) a virtual absence of thermal distortion can be obtained. This is of great advantage in maintaining the position precision required for proper assembly jigging.

The structural components can be fabricated from materials having cross-sections similar to standard extrusions (e.g., L shape, channel, T-shape, tubing, etc.), assembled by bonding or by means of suitable fasteners.

The design of the head members of the main frame provides for easy transport of columns from the canister assembly mechanism to the location on the platform under construction. The gimbal joints provide two degrees of rotational freedom with the torsional degree of freedom locked by an

anti-rotation scissor. This special restraint is required to resist the torsional loads induced by the column insertion mechanism without interfering with the other two degrees of rotational freedom. Typical arrangement of a scissor is shown on Fig. 16. Each gimbal joint is controlled by a set of two electric linear actuators which must be capable of providing rotations of 60 degrees in each plane.

The operational flexibility of this machine is such that all required maneuvers can be accomplished very simply while maintaining contact with the platform at four points in all cases. This advantage is reflected in the possibility of linking the swing arms in pairs, as shown on Fig. 16 and 17, by members which may be fabricated from standard columns with appropriate end fittings. The presence of these tie-rods provides for a more accurate positioning of the node retainers in the upper and lower parallelograms.

A peculiarity of this machine is that all rotations are performed over repeated angles of 60 degrees or near 60 degrees except in one case where the main frame must be squared. It appears possible to set up a system of locks by which accurate positioning can be controlled without complicated devices. Position control by laser beams, however, provides better means of verifying the precision of the machine geometry.

For the larger assemblers (longer columns) which must operate in a free-free mode, it will be necessary to consider the installation of a computer compartment which could be mounted on the lower main frame. Smaller assemblers designed for operation from the Space Shuttle, as shown on Fig. 18 and 19, may be controlled from the cockpit computers via a suitable umbilical.

Electrical power must be supplied to the assembler either externally via an umbilical connecting it to a power module (e.g., the 25 kW Power Module) or to the Space Shuttle. Another alternative consists of installing appropriate solar arrays on the assembler itself, locating them where they would not interfere with column manipulations or displacements of the machine.

5.1.4 Assembler Stowing and Deployment

The structural design of these assemblers is strongly influenced by the stowing requirements aboard the Space Shuttle, the deployment on-orbit, and the restowing (at least for the smaller machines). In general, the folding structure concept is based on hinged components powered by springs and automatically engaging locks. After deployment, an EVA will be required to inspect all locks and ensure specified preloads are set.

The basic Warren truss has a square or rectangular cross section with the four sides hinged upon each other in such a manner that they can be folded flat. This technique, which is described in further detail in Appendix A, provides a simple solution to the deployment of these trusses by simply releasing the spring powered hinges. Rigidity in the deployed position is insured by the use of folding diagonal members which are also equipped with over-top-dead-center spring loaded locks. The general configuration of this device is shown on Fig. 20, which indicates how a compact stowing can be achieved.

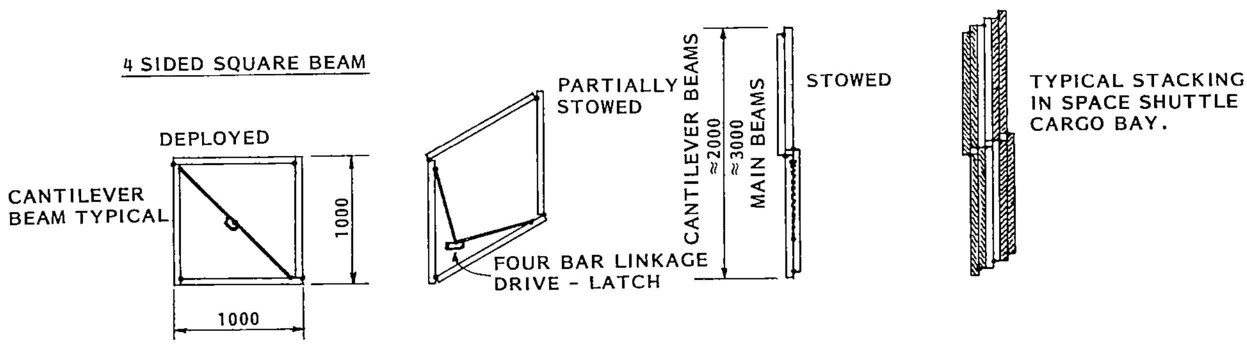


Figure 20. Beam Stowage.

The problem however, is complicated by the desirability of stowing the whole machine in one single package. The required technique is described in two steps.

1. Stowage and deployment of a long Warren truss beam. The schematic of Fig. 21 shows that the beam may be split into 2 or 3 collapsible elements which can be folded upon each other over suitably located spring powered hinges once each element has been flattened. Upon release, the beam deploys two ways simultaneously and locks itself into a rigid member.

2. The second step to be considered is the folding of a quadrangle. This is achieved by splitting each side into 2 or 3 elements such as described above and folding as shown on Fig. 22. Gimbal joints and associated mechanisms must be designed to allow the required motions, and the deployment system may be fitted with dampers to control the extension velocity and prevent detrimental impact loads. The swing arms can be folded independently then rotated against the quadrangle pack. Judicious design of such a deployable system should permit stowing within the available volume in the Space Shuttle cargo bay. The deployment can be automatic upon release of one or several locks.

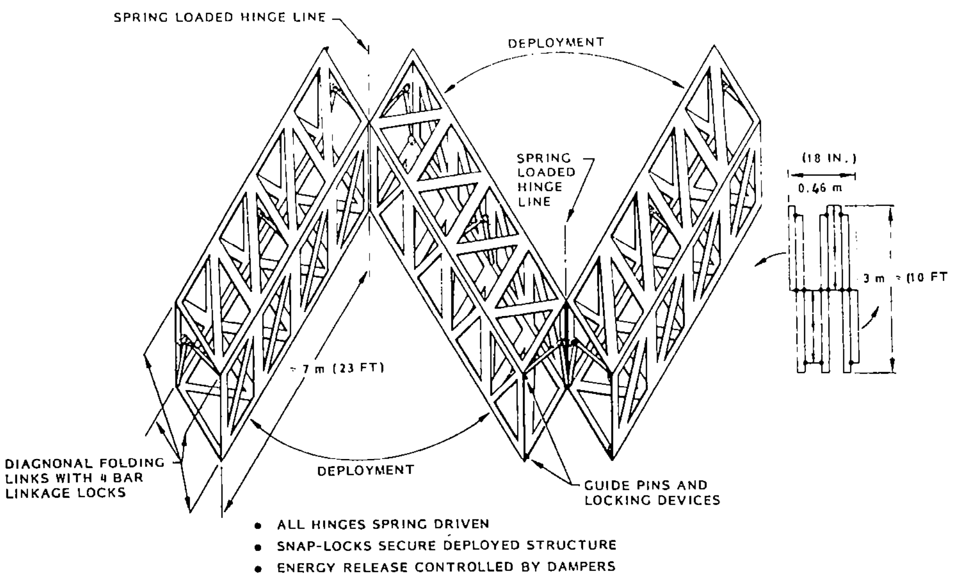


Figure 21. Schematic of Stowage and Deployment of a 21 m Structural Member With 1.5 m X 1.5 m or 2 m X 1 m Cross Section.

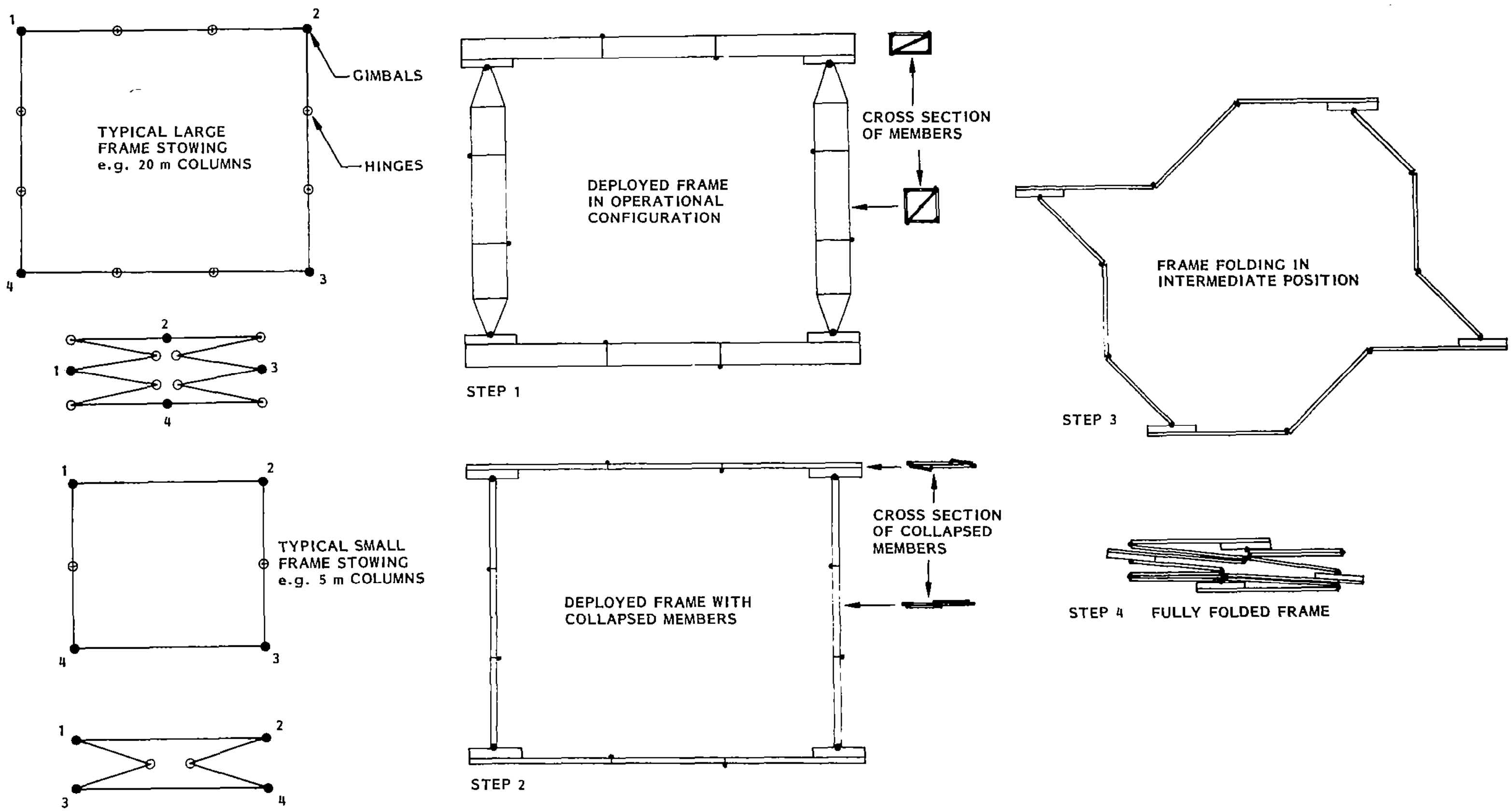


Figure 22. Schematic of Assembler Quadrangle Stowing Technique.

Restowing On-Orbit

Unless significant additional mechanical complexity can be accepted, it does not appear practical to design an automatic restowing system. Such a possibility exists, at least partially for the smaller machines which are intended for operations attached to the Space Shuttle, but EVA will still be required to perform a number of auxiliary functions such as unlocking latches, disconnecting utilities, removing computing boxes, power packs, column connection mechanisms and other robotic machinery which cannot be left on the main frame for restowing. Clearly, a special study is needed to define and examine the problems involved in restowing such a machine. Other associated problems are the capture and restowing of a large free-flying machine which may be more dependent on EVA and require special equipment to be folded. For example, it may be useful to free all or some of the hinge driving springs to reduce the folding forces.

5.1.5 Installation of Equipment

The folding characteristics of these machines will make it difficult to stow them fully equipped. A number of mechanical components will have to be added after completion of the deployment. Furthermore all operational mechanisms and power trains must be easily replaceable on orbit (Orbit Replaceable Unit - ORU) in case of malfunction. Easy accessibility to all equipment must be designed into the system as well as facilities for simplified removal or replacement procedures. Following is a list of equipment which would have to be added manually in most machine sizes.

- Outboard node joint retainers (4)
- Tie Rods (2)
- Computer package (1)
- Column assembly systems (8)
- Column transporter systems (8)
- Column insertion mechanisms (16)
- Column canisters

- Node joint distribution mechanisms (8)
- Node joint canisters (8)
- Laser alignment systems electronics (1)

The following ORU equipment may or may not be part of the basic deployable system.

- Gimbal actuators
- Power units (electric motors, gearboxes, etc.) for a variety of mechanisms
- Mechanical devices of the column and node joint distribution and insertion systems, of the swing arms drives, and of other mechanisms
- Electronic boxes
- Umbilical connectors
- Other devices undefined at this conceptual stage of the Study.

5.2 OPERATION OF THE GIMBALLED PARALLELOGRAM ASSEMBLER

5.2.1 Traverse and Row Change Motions

Two types of traversing modes are shown on Fig. 23 and 24. The flexibility afforded by the gimbals makes it possible to align the machine geometry with all cases of oblique columns. On Fig. 23 the assembler is shown with the gimbals at 30 deg lateral to match the set of oblique core columns, while on Fig. 24 the gimbals are at zero deg to match the set of normal core columns in the alternate traverse.

The machine is attached to the platform under construction by means of the node joint retainers which have the capability of releasing themselves from a set of nodes and capturing another set as the machine translates along the edge of the platform. In order to keep the platform under control at all times, a maximum of four node joints can be released simultaneously. Then the machine has the ability to rotate in various ways about the four held joints thereby achieving several types of translation to perform lateral as well as backward traverses. In these traverses, the number of columns which may be inserted varies from 3 to 5 and the design virtually eliminates the risk of interference from the column transport system such that simultaneous insertion can be performed with a significant reduction in construction time.

A coordinate system (x, y, z, α, β, γ) (Fig. 17) has been selected to provide easier reference for understanding the various motions. It should be noted, however, that rotations α and β are always combined due to the skewness of the geometry. Rotations γ are always single and all rotations are performed within arcs of 60 degrees.

Shown on Fig. 23, the machine advances along the edge of the platform under construction by swinging alternately (Rotation β) about the two upper gimbals, then about the two lower gimbals. In Fig. 23, it is shown at the completion of a right hand traverse inserting the 3 columns marked by ∇. The general traverse motion is a combination of the advancing motion described above while

simultaneously swinging the upper and lower parallelograms (Rotation α) in order to insert all columns of the upper and lower platform surfaces. Many of these maneuvers can be combined and a detailed motion study will be required to define the most efficient sequence.

The second traversing mode is shown in Fig. 24. In this case, the main frame is squared and locked in this position. Traversing motion is performed by the swing arms (Rotation γ) and a complete cycle consists of two steps where the arms rotate alternately about the outboard or the inboard node points. Columns can be inserted simultaneously or with a time separation of 10 to 15 seconds wherever a risk of interference exists.

Row change or backward traverse is shown on Fig. 25 to illustrate the capability of this machine to build a beam element which may be the start of a platform. The beam cross section shown here is the minimum section which can be made with this machine, and provides enough node joints for safe operation. The general motion consists of 6 steps per cycle during which 17 columns are inserted to advance the beam by one column length.

A simplified motion study, shown on Fig. 25 has been performed to ensure the feasibility of this operation and gain an insight into at least one sequence of assembly. The complete cycle consists of 6 steps; the last two steps, being independent, can be performed simultaneously.

<u>STEP 1</u>. Main rotation β about the lower gimbal points C and D. Three columns, marked 1, can be inserted, two of them simultaneously.

<u>STEP 2</u>. Main rotation α about the upper gimbal points A and B. Two columns, marked 2, can be inserted simultaneously.

<u>STEP 3</u>. Main rotation β about the upper gimbal points A and B. Five columns, marked 3, can be inserted, four of them simultaneously.

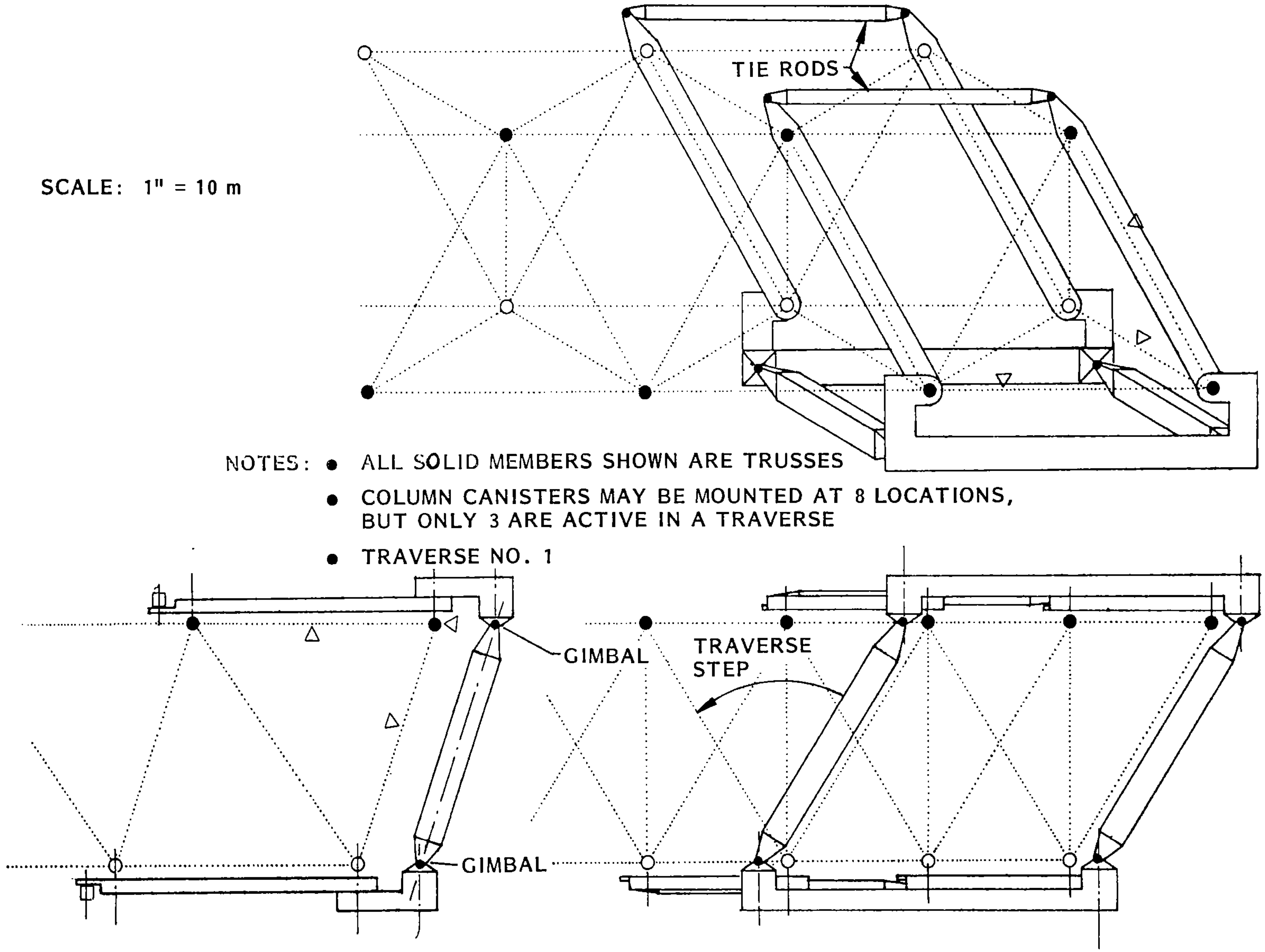


Figure 23. Large Space Structure Gimballed Parallelogram Assembler Schematic of General Layout.

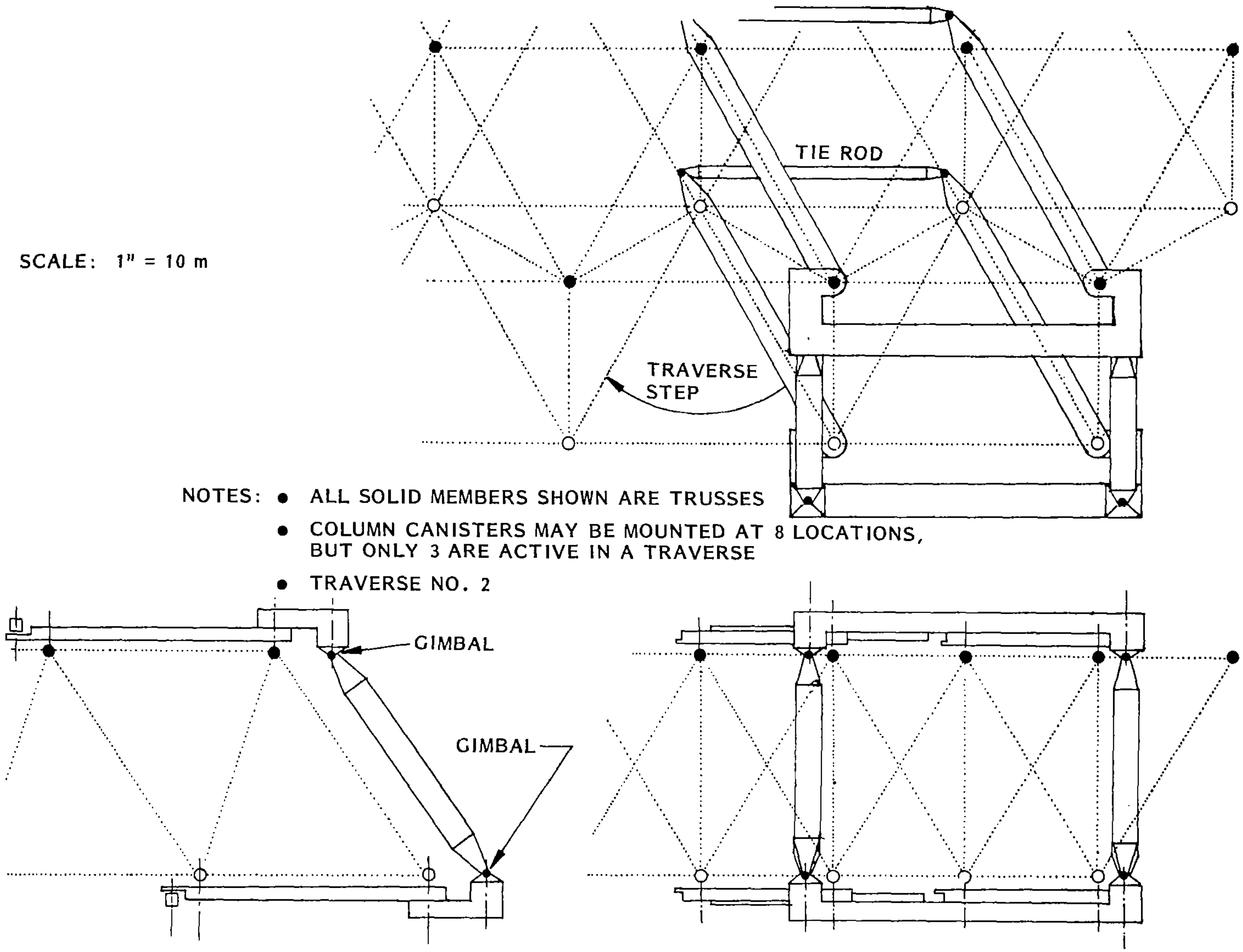
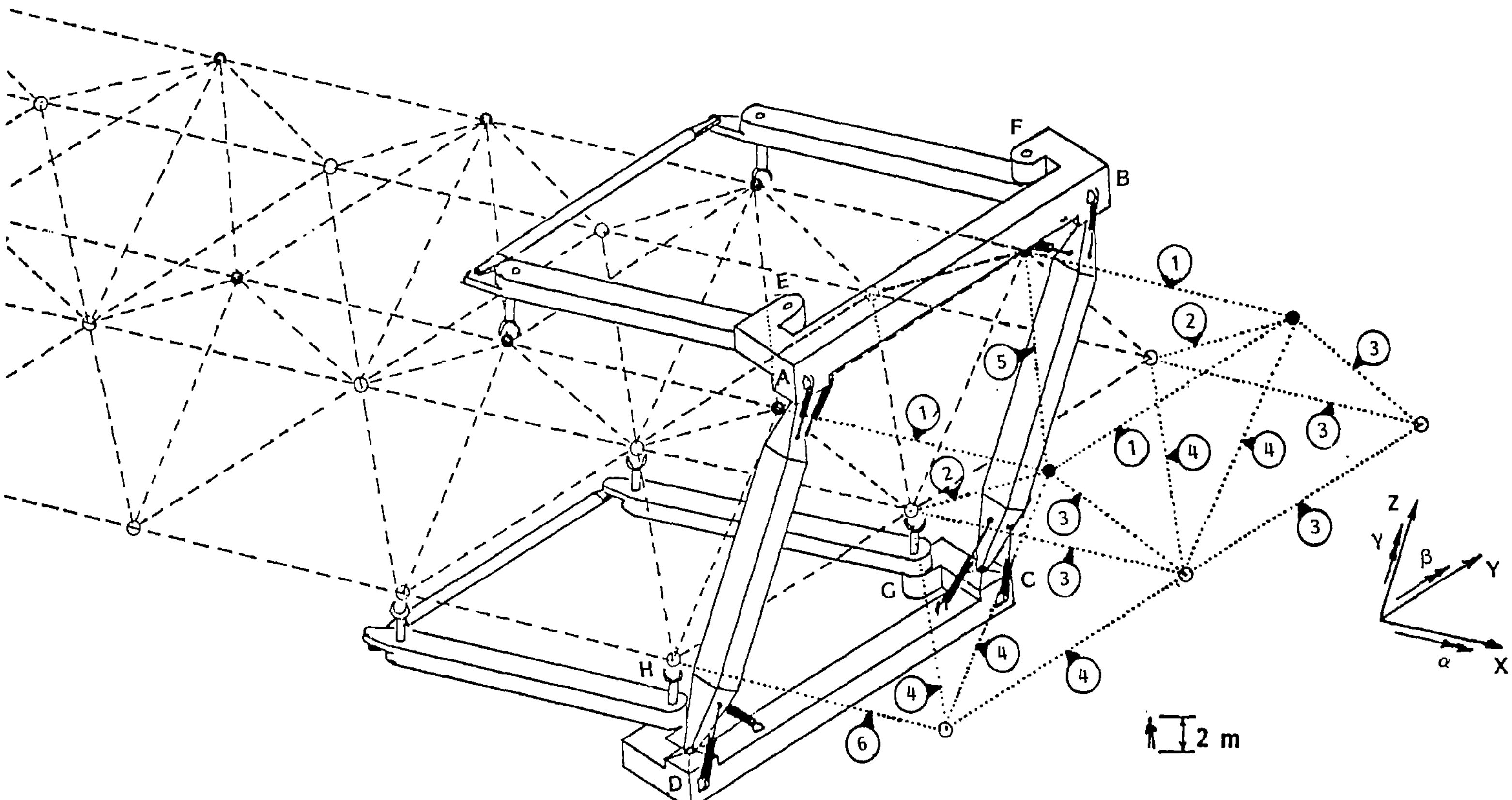


Figure 24. Large Space Structure Gimballed Parallelogram Assembler Schematic of General Layout.



STEP	ROTAT. ABOUT	NO. COL.	ROT. TIM. MIN.	COL. INS. MIN.
1	β C&D	3	1	1
2	α A&B	2	1	1
3	β A&B	5	1	1.25
4	α A&B	5	1	1.25
5	Y E&F	1	1	1
6	Y H&G	1	1	1
TOTAL		17	6	6.5

STEPS 5 AND 6 CAN BE PERFORMED SIMULTANEOUSLY

17 COLUMNS CAN BE INSERTED IN APPROXIMATELY 10.5 MIN

STANDARD 2700 COLUMN LOAD IN 27.8 HR

Figure 25. Large Space Structure Gimballed Parallelogram Assembler Operation Motion Study.

STEP 4. Main rotation α about the upper gimbal points A and B. Five columns, marked 4, can be inserted, four of them simultaneously.

STEP 5. Rotation γ of the upper parallelogram about points E and F. One column, marked 5, can be inserted.

STEP 6. Identical to Step 5 for the lower paralellogram about points H and G; one column, marked 6, can be inserted.

This completes one cycle in which 17 columns have been inserted to advance the beam by one column length (20 m). Therefore, a nominal 2700 column payload would construct such a beam about 3170 m long, and 40 m wide on the larger face.

Construction of a platform can start by assembling such a beam to the length of a side then turning the machine 90 deg to start traversing as shown in Fig. 23 and 24.

Other geometry, such as triangles and hexagons can be erected, as well as open structure, using the beam shown on Fig. 25 as the main element. For example, a hexagonal toroid could be constructed with a side length of about 500 m.

5.2.2 Construction Time

It is assumed that the average angular velocities are 1 deg/sec and that columns can be transported from the canister and set in place in 60 seconds. The data presented on Fig. 25 and summarized below, are based on these assumptions. These data assume that steps 5 and 6 can be performed simultaneously.

Step	Number of Columns	Rotation Time (Min)	Column Insertion Time (Min)
1	3	1	1
2	2	1	1
3	5	1	1.25
4	5	1	1.25
5 & 6	2	1	1
Totals	17	5	5.5

Therefore, 17 columns can be inserted in 10.5 min, and the standard 2700 column load in 27.8 hr.

5.2.3 Comparison With Previous Concepts

The following table provides a comparison of the construction time requirements for the erection of a full Space Shuttle load consisting of 2700 complete columns and 600 node fittings with the gimballed paralleogram assembler and the earlier concepts described in Appendix A.

	Gimballed Parallelogram	Rigid Parallelogram
	(HR)	(HR)
Traversing Time	13.2	31
Column Insertion	14.6	18.4
Assembler Loading	8.0	24 to 48
Totals	35.8	73.4 to 97.4

The gimballed parallelogram assembler reloading time is considerably less than that of the earlier design because the mechanical assembly of half-columns is performed directly on the machine using the most appropriate scheme described in Appendix B. In this case, loading need only be performed once for each Space Shuttle load. Therefore, machine loading and platform construction using a full cargo bay of joints and columns can be accomplished in less than 2 days.

5.3 HALF-COLUMN ASSEMBLY

The half-column assembly (Scheme No. 8, Appendix B), selected for application to the gimballed parallelogram machine presents several advantages over the various schemes examined in the trade-off study. The total length of these devices always exceeds that of the machine components to which they are attached. It is therefore necessary to hold the excess length to a minimum which is shown, in the trade-off study, to be about 1 2/3 column lengths (33.5 m for 20 m columns). At the same time, it is desirable to reduce as much as possible the rotational moment of inertia of the swing arms about their hinge points. This requirement implies concentration of the masses close to the hinge lines. The selected scheme, which is shown on Fig. 26, provides a good compromise, since the double column canister is located at one end of the device and the lighter track mechanism extends only one half-column length outboard of the supporting structural component in the inactive mode. In the active mode, the column and its supporting bracket extends for a short period of time another half-column length, making the total clearance required 1 2/3 column lengths.

This half-column assembly machine consists essentially of a tracked column carrier and a double canister which contains two stacks of nested half-columns, stored in opposite directions as shown on Fig. 26. The canister is equipped with a driving mechanism designed to advance the column stacks one step at a time. This advance mechanism can be powered from the carrier track via a simple dog clutch system. The canister does not need to carry any separate power system; a simple mechanical connector is sufficient.

The carrier mechanism performs all the functions required to capture, assemble and transport the half-columns to a position where they can be collected by the insertion mechanisms. The sequence of operation is as follows.

- The advance mechanism moves two half-columns to the capture position.
- Carrier captures the small end of one half-column.

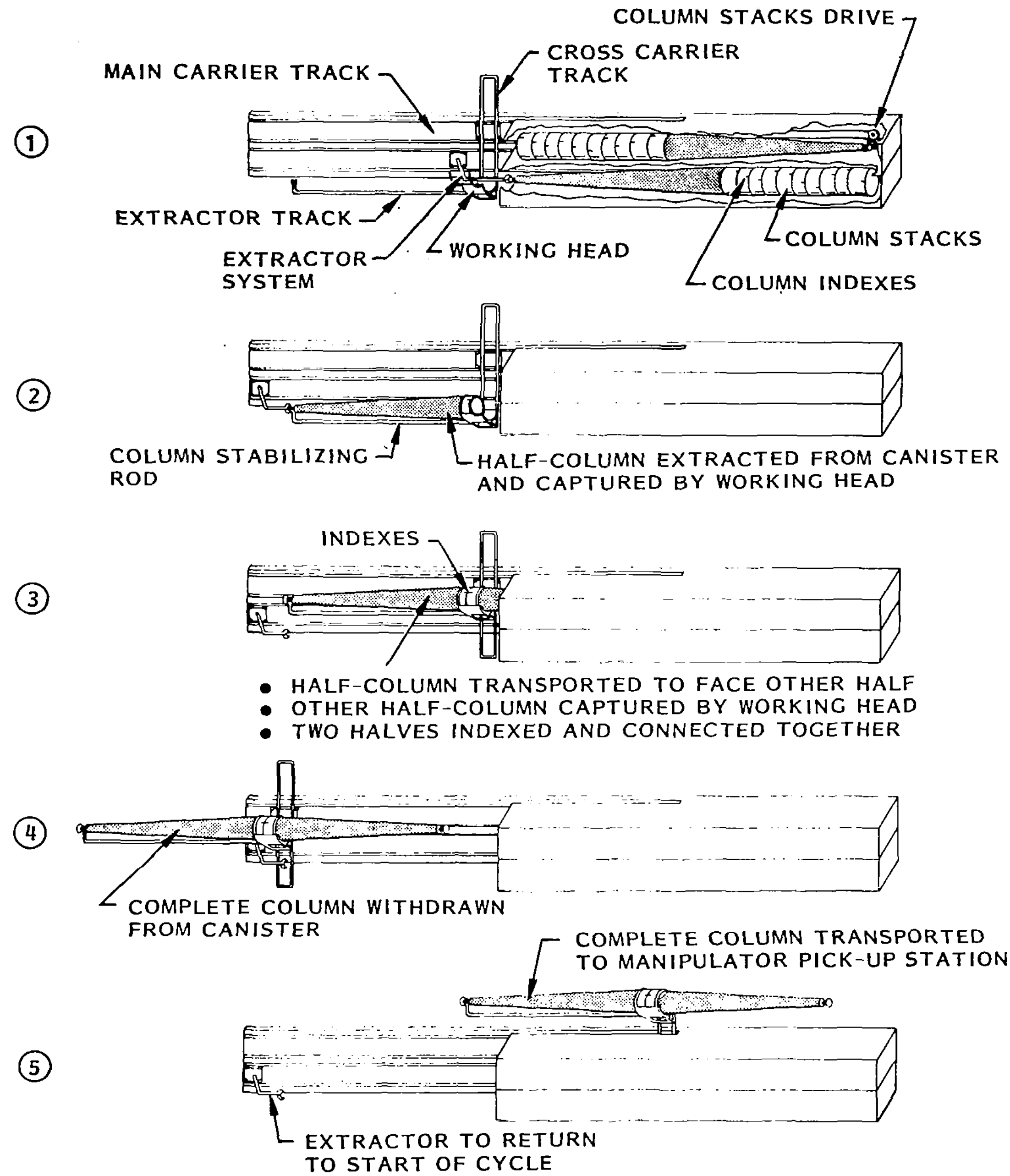


Figure 26. Column Assembler Operation.

- Carrier draws out the half-column and captures the large end into the working head (see details of working head Figs. 31 and 32.)
- Carrier moves up along its vertical track to place the working head facing the large end of the other half-column.
- Carrier moves in so that the working head will capture the large end of the other half-column.
- Simultaneously, carrier draws out the second half-column; the working head rotates both components to align their markers and plug them into each other. At this stage, the column is assembled.
- The small end of the second half-column is captured by the carrier stabilizer.
- The carrier moves along its vertical tracks to place the column above the canister.
- The carrier transports the column to the insertion mechanism capture position by a translation along its longitudinal track.
- With the column securely held by the insertion mechanism, it is released by the working head and stabilizer, and the carrier returns all mechanisms to the start of the cycle.

Multi-row canisters are feasible. They will require additional internal mechanisms to move the column stacks to the pick-up position. This device would also be operated from the carrier track in order to simplify the design of the canisters and reduce dead weight to a minimum.

The advantages of this system are:

- Simple, single canister design.
- Small dimensions of the canisters, which facilitates handling, saves volume, and saves weight, thereby improving packaging in the Space Shuttle.
- Reduced complexity of the carrier mechanism.
- Column manipulations under firm control of the working head, leaving the column ends free for capture by the insertion mechanisms.

- Stability during transport provided by column end holders, which eliminates undesirable vibrations.
- Carrier mechanism directly accessible for on orbit servicing or replacement, independent from canisters.
- Identical carrier mechanism at all loading points. Only one type of spare replacement unit needed.
- Canisters can be adapted to also carry utility harnesses for installation upon command on any column.
- Design amenable to at least partially automatic utilities harness installation.

Typical Half-Column Center Fitting

A typical column center fitting is shown on Fig. 27. This fitting is based on a NASA Langley Research Center Drawing (NASA LD-415003), modified by adding a capture groove designed to provide a solid handling surface which does not interfere with the graphite/epoxy structure.

An indexing mark, compatible with the use of an electro-optical sensor, is painted on one of the teeth as shown on Fig. 27. These fittings are designed to permit the stacking of the columns in "plastic cup" fashion as shown on Fig. 28. The stacking pitch is about 76 mm (3 in.) regardless of column length.

The mode of connection of these fittings is shown on Fig. 29 and 30. On Fig. 29, the two fittings are shown head-to-head, with their indexes in the proper position and ready to be inserted. Figure 30 shows the fittings connected together and locked.

Note that separation of these fittings is normally accomplished by a specially designed tool that simultaneously opens all hooks and separates the two halves. In the design of such a tool, attention must be paid to the aluminum alloy fitting. The hooks cannot stand large deflections without yielding, and the tool must limit this deflection to the minimum required for withdrawal.

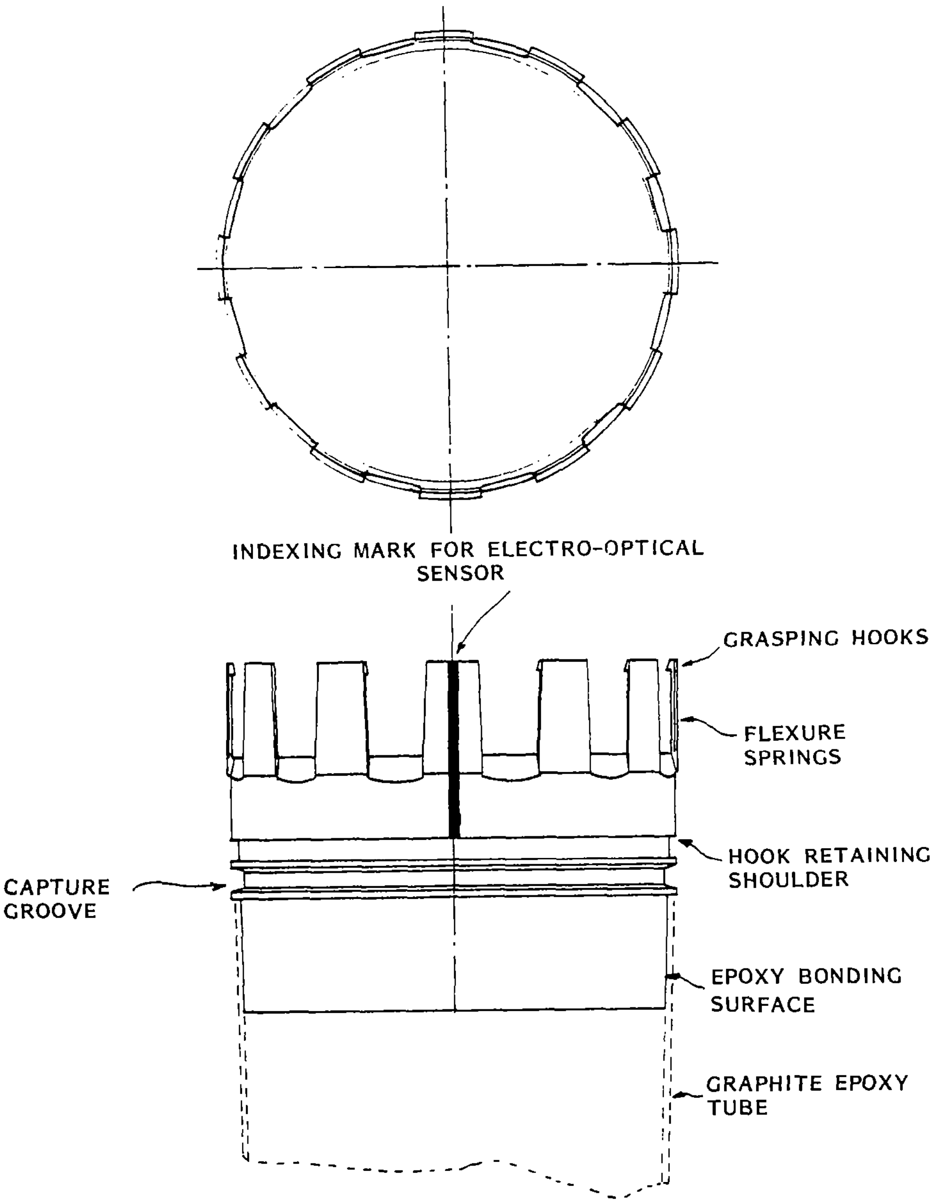


Figure 27. Typical Column Center Fitting.

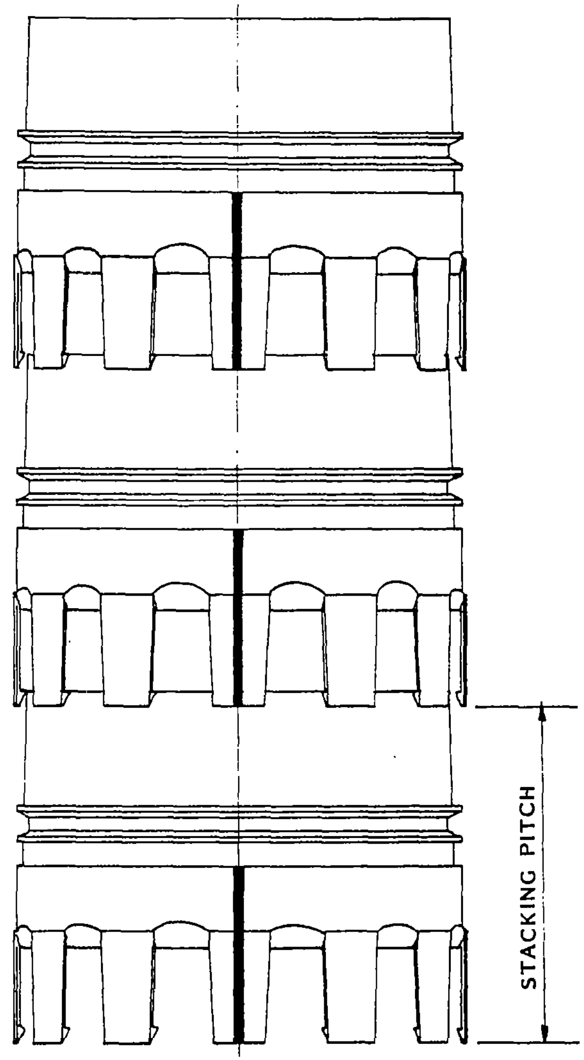
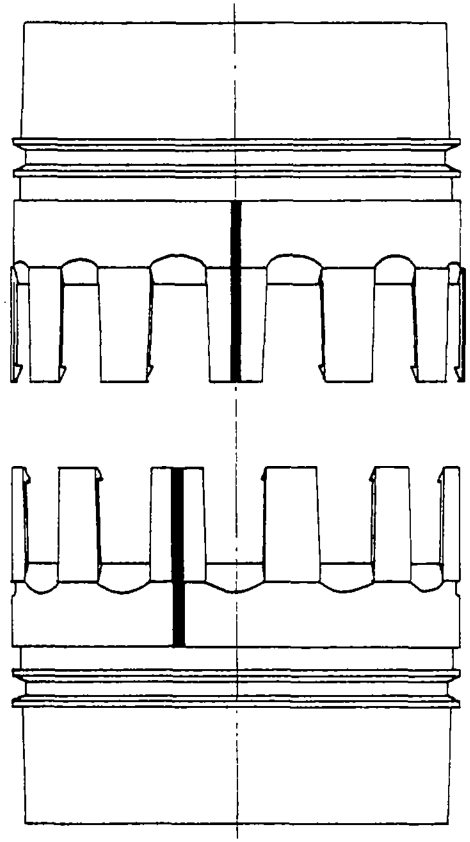


Figure 28. Half-Column "Plastic Cup" Stacking.



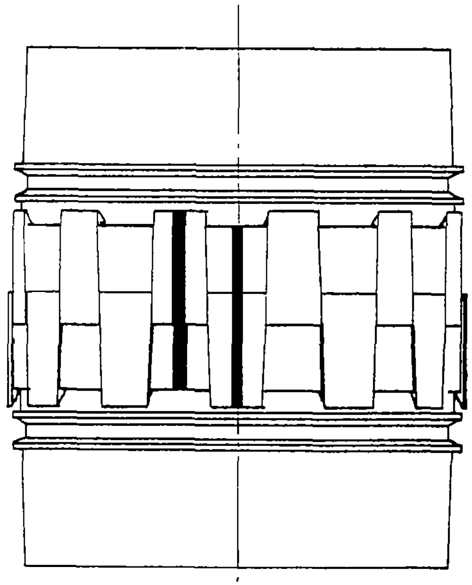


Figure 29. Indexed Half-Columns at Assembly. Figure 30. Column Center Connector Assembled.

Positive guidance is also necessary to ensure clean separation of the two halves. Normally, however, these fittings are not designed for separation.

Working Head Design Concept

The sequence of operations required to capture the half-columns, extract them from the canister stacks, manipulate, connect, transport, and finally release them, is shown on Fig. 26.

Figure 26 (operation 1) shows the extraction of the lower half-column pulled by the small end. It is withdrawn through the working head which secures it automatically as it reaches the position of Fig. 26 (operation 2). As soon as this is accomplished, the vertical carriage transports the half-column to face the large end of the other half as shown on Fig. 26 (operation 3). The canister advance mechanism is then activated to move the column stack by one step thereby aligning the large end of the column with its side of the working end. Once both half columns are secured by the working head, they are rotated individually to orient their polarizing marks, then the ram mechanism plugs the connectors in and the carrier system completes extraction and transport of the column.

Conceptual Design of Working Head Mechanisms

The general concept of the working head mechanism is shown on Figs. 31 and 32. The ram transit mechanism is presented on Fig. 31 and the capture and roll-indexing systems on Fig. 32.

The capture groove added to the NASA fitting is used in conjunction with a set of four rollers which provide both radial and axial restraints. One of these rollers is powered to roll-index the fitting. Indexing is performed by means of an electro-optical system which controls an electric motor and stops the rolling when it detects the mark.

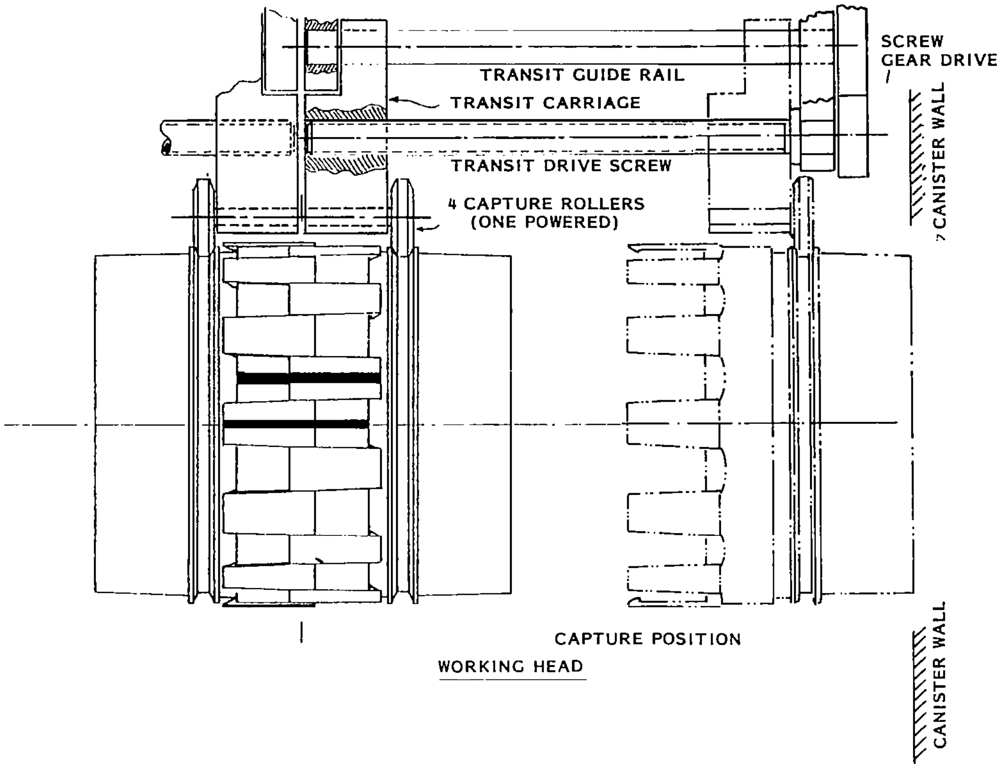


Figure 31. Working Head Mechanism (Side View).

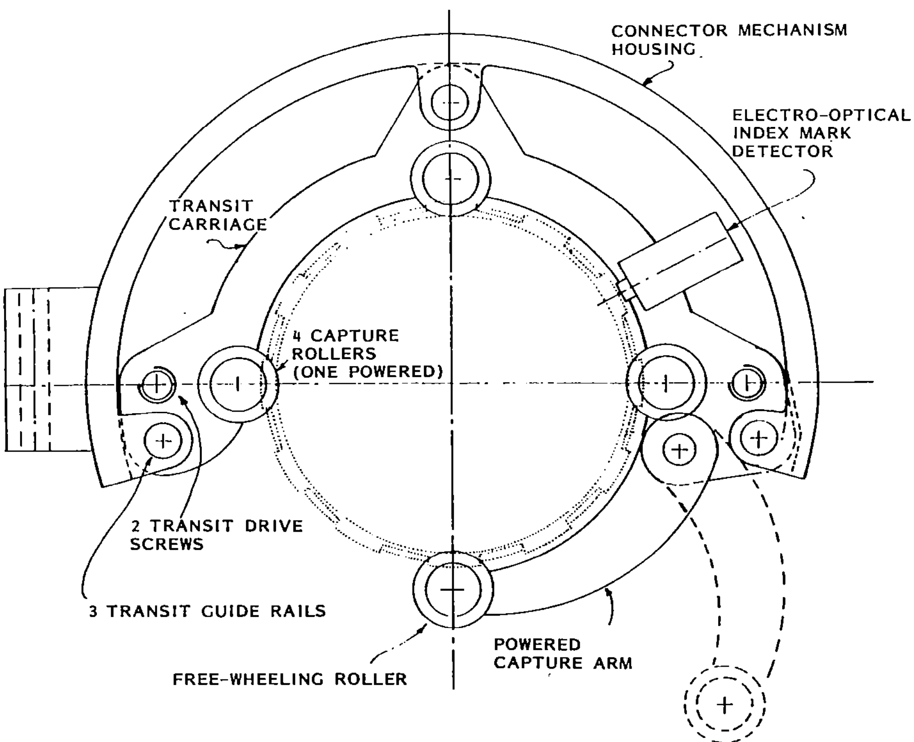


Figure 32. Working Head Mechanism (End View).

The transit system consists of a set of two drive screws and three guide rails. The guide screws are powered and should preferably be cross-linked mechanically (gear train or otherwise) to ensure parallel motions. Alternately, separate stepper motors may be synchronized electronically. The choice of the appropriate system may be dictated by the space available within the working head, which must be as compact as possible.

In this design, the need for compactness is derived from the influence it may have on canister design and on the associated column carrier system. The space between the half-columns must be related to the working head size in order to prevent mechanical interferences and waste of space in canister design. Compactness, also, helps in designing the column carrier system; by avoiding excessive overhangs, a more rigid system can be achieved.

After due consideration, a four-roller system was selected in preference to three-roller design, in order to ensure a better alignment of the column fittings during transit and lockup. The capture mechanism imposes the necessity to open one side of the housing, therefore compliance is increased in the capture arm hinge and drive system. Thus, in a three-roller design one roller would be soft mounted by comparison with the other two, which would be hard mounted. This could lead to a dissymmetric pull on the half column, preventing proper engagement of the column fittings. In the four-roller system shown on Fig. 32 the main axial force is applied along a diameter by two hard mounted rollers adjacent to the transit drive screws. The upper roller, also hard mounted, provides the necessary stability about the other axis. The soft mounted roller of the capture arm need not contribute to restraining the pitching moment.

The electro-optical index mark detectors must be offset by half a tooth between the two halves of the mechanism in order to correctly align the column fittings for insertion and lockup. The swinging capture arm is powered by an independent motor.

The complete mechanism is enclosed in a rigid housing (turtle shell housing) as shown on Fig. 32. This housing is equipped with a powered locking system in the deployed position such that the column fitting lockup preload is correctly reacted.

Working Head Positioning with Respect to Column Canister

Due to the particular design of the half column fitting capture groove, positioning of the working head must be fairly precise; a tolerance of $\pm$ 1.5 mm (1/6 in.) appears necessary. This problem has not been addressed in detail in this Study because its solution depends largely on the detail design of the canisters and their internal mechanical drives, which advance the half-column stacks to the capture position. Nevertheless, a fairly simple solution using a system of guides and stops probably can be found.

Remarks

The results of this conceptual study indicate that the half-column large end fittings, as shown on NASA LD-415003 drawing, could be modified to include a handling surface distinct from the connector system on one side and the graphite epoxy column on the other side. This is achieved by adding about 10 mm to the fitting length. Within this length, a V-groove is built up to match a set of rollers in the assembly machine working head.

With these modified column fittings, the mechanism presented here has the capability to automatically perform all the necessary manipulations to plug the half-columns into each other and apply the required lockup preload.

5.4 COLUMN INSERTION MECHANISMS

These devices are simplified versions of the Space Shuttle Remote Manipulator System (RMS). They must be designed to transport the completed columns from the end of the column assembly carrier, travel to their location on the platform under construction, and perform the necessary steps to insert and lock the column ends into the node joint sockets.

In formulating the concept of the platform assembly machine, care has been taken to ensure similar geometry at all stations in order to use identical manipulators at all points. Thus, only one unit need be designed which can adapt to minor variations through software control. The motion of these insertion mechanisms, in line with the overall concept, is under computer control, with manual override and back-up.

The general scheme of these mechanisms is shown on Fig. 33. It is based on the concept design of the previous assembly as shown in Appendix A. Essentially, it is a rigid arm with motorized pivots at the shoulder, elbow, and wrist. By combining rotations about elbow and shoulder, the column can be secured from the carrier, transported along a precise trajectory, and brought to the node joint approaching in the correct right direction for plug-in. Fine tuning of the position can be achieved by means of the wrist, which can provide two degrees of freedom (rotation and axial (lateral) translation) to accommodate dimensional variations.

Plug-in force could be reacted through the node joint retainer. However, it is considered much better to equip the insertion mechanism end effectors with a squeezing device to dissociate these loads from the general structure which is considered too flexible for satisfactory operation. Several devices can be adapted for this purpose.

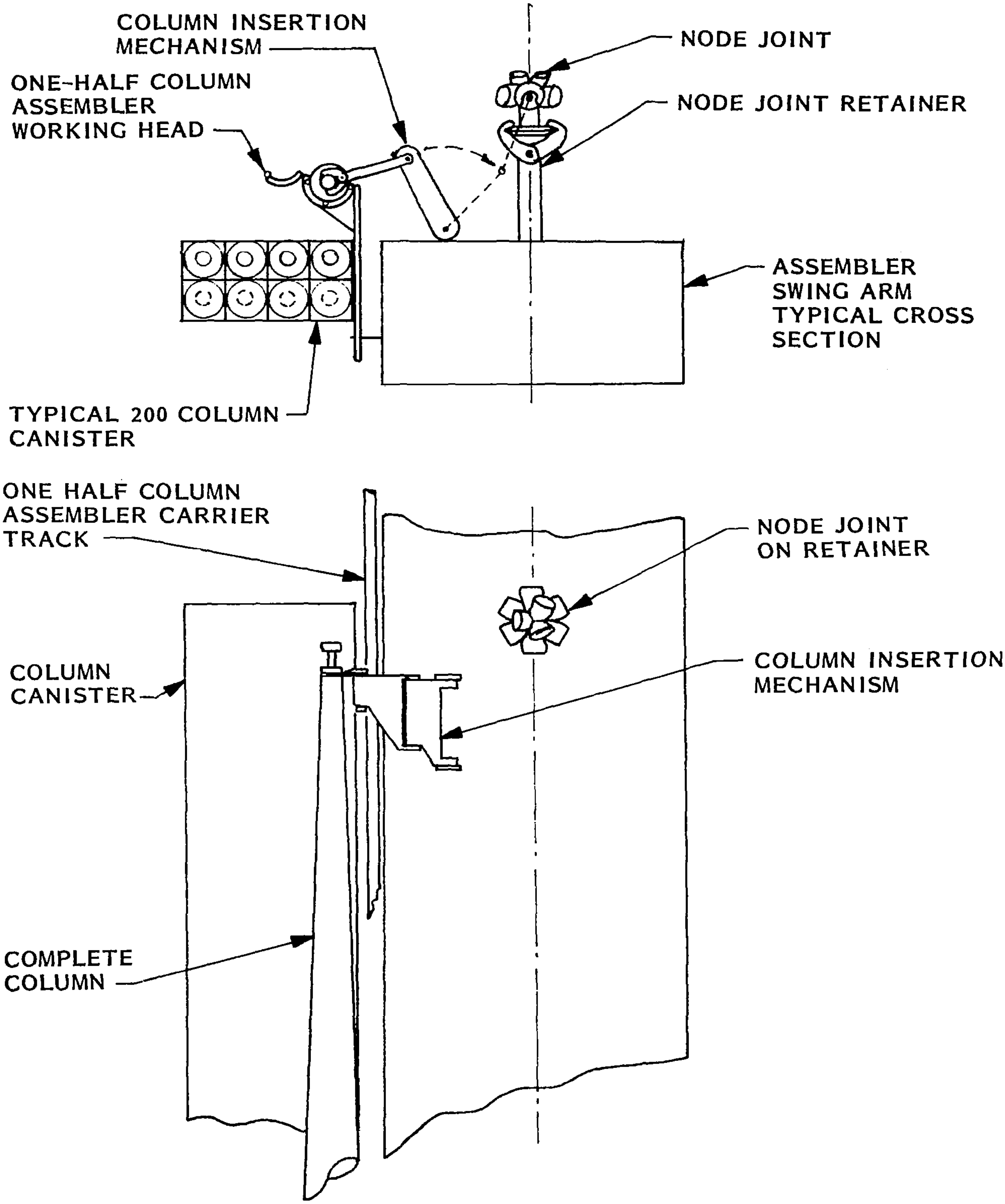


Figure 33. Column Insertion Mechanism.

5.5 NODE JOINT RETAINERS

The general concept of the node joint retainers was defined in some detail at an early stage of the Study. Variations of the design will be found in Appendix A. The node joint retainer must perform several functions in two distinct modes of operation; machine translation and platform construction.

In the machine translation mode the retainers must be able to capture an already installed node joint, use it as a reaction point to displace the machine with respect to the platform, then release it to repeat this operation at the next node. In addition, the mechanism may, in some cases, be required to apply driving torques to rotate part of the assembler during some particular maneuvers.

In the platform construction mode, the retainer must be capable of securing a node joint from the nearby canister, rotate it to a specified orientation, then transport it to its location in the framework. This "jigging" must be accomplished with a precision of the order of $\pm$ 1 mm with respect to the assembler references. The retainer must then be held rigidly enough to withstand column insertion loads.

A typical retainer mechanism which provides two degrees of rotational freedom and operation of a prehensile claw or end effector is shown on Figs. 34 and 35. This device must be completed by an electro-optical control system which sets the orientation of the node fitting to match the requirements of its position in the Space Platform.

All electrical motors shown on Figs. 34 and 35 are drive units, each consisting of two motors (dc or stepper) and a reduction drive designed for emergency operation with one motor out. The three functions have been shown with worm drives, which present the advantages of minimum backlash and irreversibility. It should be noted also that the two functions (orientation and operation) of the retainer claw must be integrated, either mechanically or electrically. Mechanical integration requires mounting the claw drive motor on the claw rotation shaft using slip rings to supply its power.

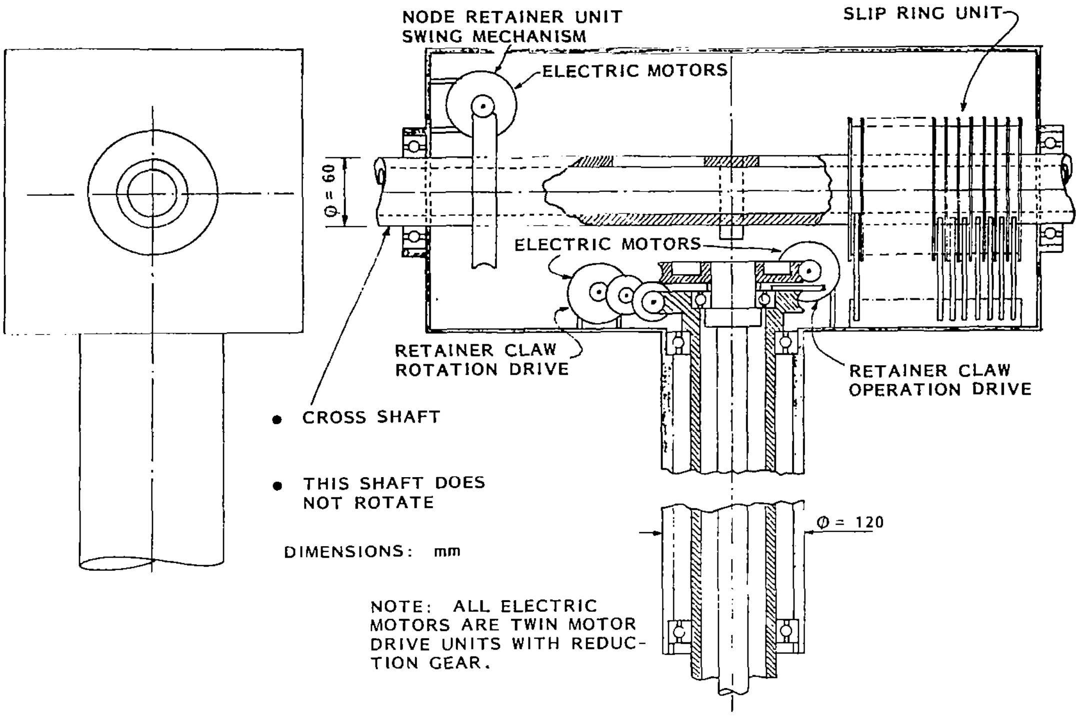


Figure 34. Node Retainer Drive Unit.

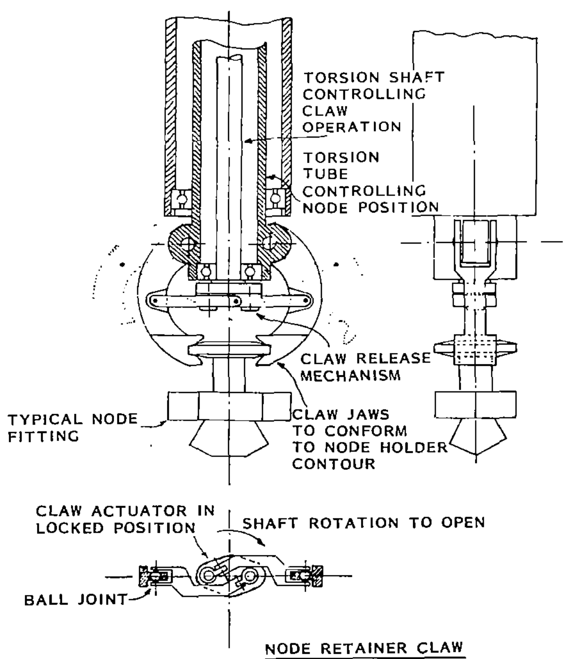


Figure 35. Node Retainer and End Effector.

The node retainer claw is operated by a rotating shaft in preference to a push-pull rod and associated scissor mechanism. This system is more compact, has better mechanical advantage and is self-locking in the closed position. The claw profile is designed to allow fairly large position tolerances in grasping the node fitting head. The double cone head ensures tight gripping by the claw.

The shape and dimensions of the housing are schematic and can be extended in any direction as required to increase internal space. The complete unit is attached manually in EVA after deployment of the machine structure, thus it is completely ORU. Since these units will be of relatively small volume, it may be possible to preinstall them in the deployable arms without sacrificing their ORU capabilities. A more advanced feasibility study is required to ascertain this.

5.6 NODE JOINT CANISTERS

The system under consideration for storing and distributing the node joints consists of individual carriages, one for each node, running in tracks and driven by cables, or preferably by a more precise network of chains and sprockets. The general appearance of this system is shown on Fig 36, which presents one option of the internal node joint circulation where each row advances toward a well into which the node carriages are driven toward a node capture chamber, where the node retainer has access. Although this advance procedure is feasible, it is thought that an alternate using a continuous endless chain is probably preferable although it does require moving the whole contents of the canister one step at a time along a "zig-zag" course. This solution would present some advantages from the standpoint of mechanical design because of the absence of separate track systems inside the canister. However, a continous switchback track with many 180 deg turns requires careful design to eliminate all possibilities of malfunction. In all cases, double chain drives are necessary and special mechanisms must be devised for restraining the node joints during launch.

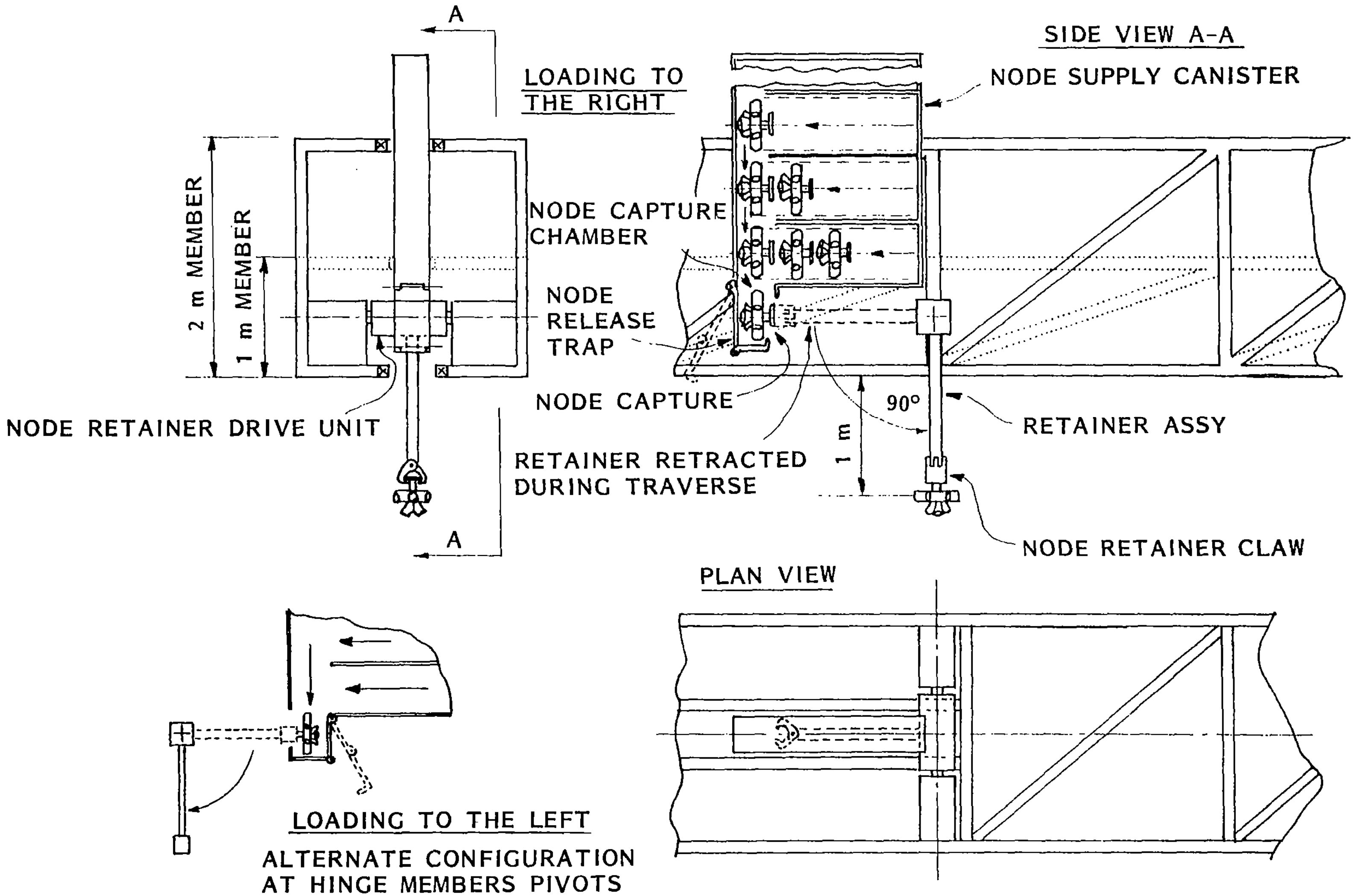


Figure 36. Node Retainers and Supply Canisters.

Section 6
PACKAGING CONCEPT

6.1 PHILOSOPHY OF OPERATION

To a large extent, the efficient utilization of the Space Shuttle cargo space is influenced by the method selected for the operation of the platform assembler. For example, it is possible to assemble a tetrahedral truss structure using the Space Shuttle RMS as the primary assembly device. For such a case, the equipment left in orbit would be necessarily idle during the 14-day rotation period of the Space Shuttle, to be followed by several days of intense round-the-clock activity. Such a cycle is not efficient, since it entails long idle periods. Furthermore, the close proximity of a large and relatively flimsy structure with the heavy Space Shuttle provides significant dynamic interaction problems.

The availability of on-orbit assembly machines provides a means of improving the efficiency of this operation by using the Space Shuttle primarily for transportation.

This concept, which underlies the operational times computed in Section 5, limits the Space Shuttle to its primary role of transporting supplies. All assembly operations are then carried out in orbit. The gimballed parallelogram assembly concept would receive a cargo bay of column elements and node joints. Assembly would take place until the columns had become exhausted (less than 2 days). During this time the Orbiter would be standing by providing assistance as required.

The column elements and node joints will be packaged in canisters or magazines and off loaded onto the beams of the assembler.

6.2 SPACE SHUTTLE CARGO BAY

The basic Space Shuttle cargo bay is shown on Fig. 37, with the OMS volume and location indicated. The total space available consists of a cylinder 4.572 m in diameter and 18.288 m long. However, the space available is reduced by the EVA tunnel, which occupies 1.219 m x 1.219 m (4 ft x 4 ft) over the diameter of the cargo bay, just aft of the cockpit. Also (optionally), the OMS kit subtracts a large volume just ahead of the fin bulkhead. This kit, which has a mass of 6,472 kg (14,255 lb), reduces the payload capabilities by 22 percent to 23,018 kg (50,700 lb).

Allowable Length

In the absence of the OMS kit, the total length of 18.288 m is available in the areas which are not occupied by the EVA tunnel. This length is reduced to 17.069 m at the back of the tunnel. The OMS takes 2.896 m, reducing these allowable lengths respectively to 15.392 m and 14.173 m.

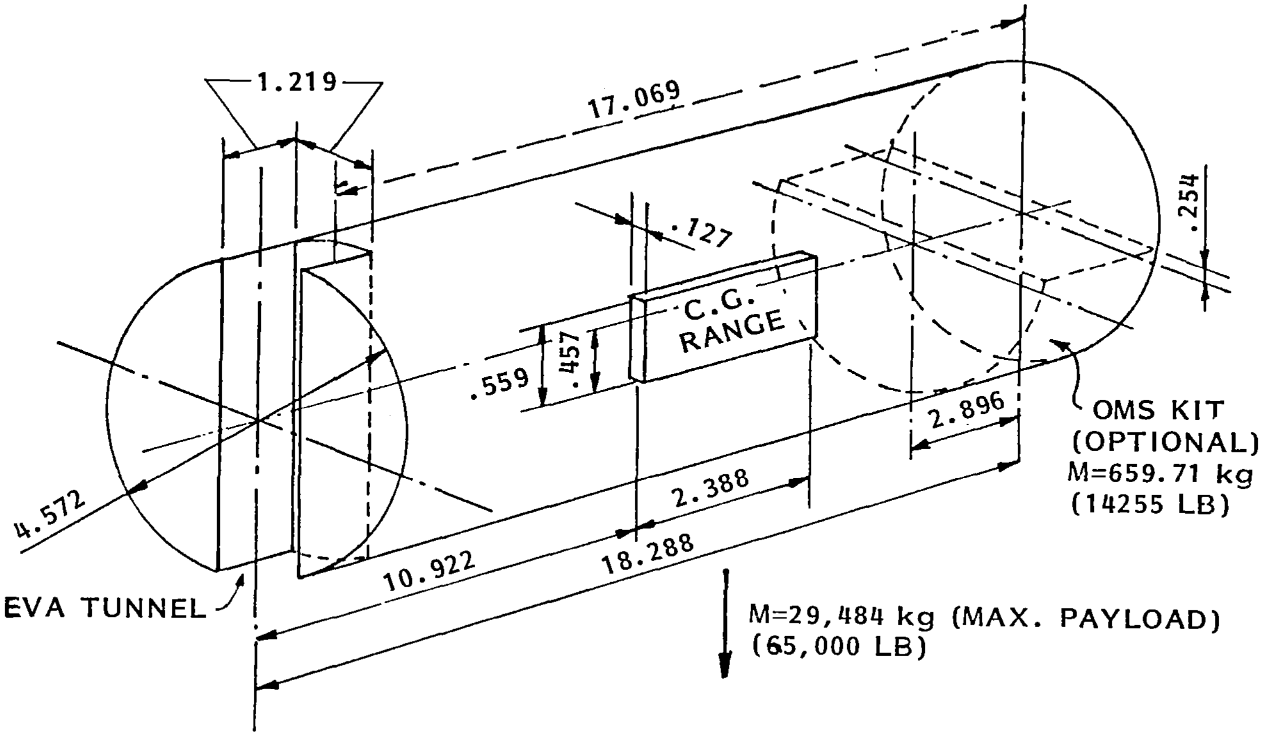
Payload C.G. Range

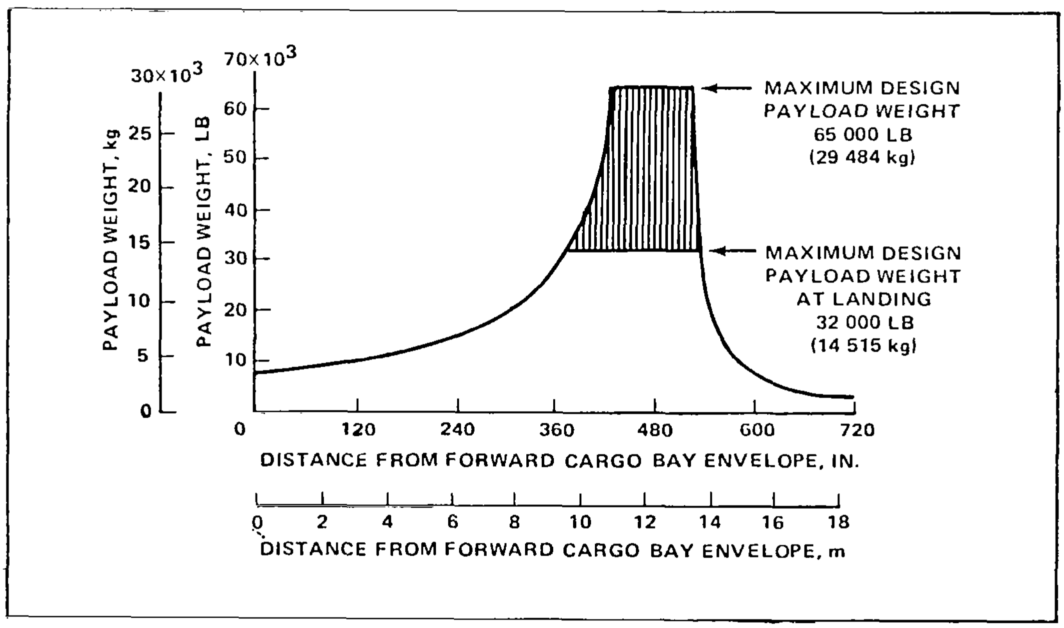
The payload c.g. range shown on Fig. 37 is applicable to the maximum payload of 29,510 kg (65,000 lb).

6.3 CHARACTERISTICS OF THE PAYLOAD

The most important parameters which characterize the payload are as follows:

- o Half-column weight, itself dependent on graphite/epoxy wall thickness and type of center connector selected
- o Half-column stacking pitch, i.e., number of half-columns which can be stacked together within a specified length





Payload center-of-gravity limits along the X-axis (X_0) of the Orbiter.

Figure 37. Space Shuttle Cargo Bay.

- Design of the canister system

- Permissible packaging geometry within the constraints of the Space Shuttle cargo bay

- Number of OMS kits required for the mission

- Constraints on the payload c.g. location to remain within the specified range (Fig. 37).

General Considerations and Assumptions

A mass properties analysis of the half-columns indicates that the weight per item could vary from 4.54 kg to 6.81 kg (10 lb to 15 lb), depending on composite wall thickness and type of connector used. The packaging study is carried out for these two extreme half-column weights.

Based on composite nominal wall thickness, but accounting for out-of-round and other tolerances, the minimum stacking pitch is found to be 112 mm (4.43 in.). Therefore, column stacking within the length separating the aft end of the EVA tunnel and the cargo bay half bulkhead allows 57 half-columns per stack. The following table summarizes the mass properties of such a stack.

	Minimum Weight Columns	Maximum Weight Columns
One half-column	4.54 kg (10 lb)	6.81 kg (15 lb)
57 half-column stack	258.78 kg (570 lb)	388.17 kg (855 lb)

If an OMS kit is used, the available length is reduced by 2.896 m for about 55 percent of the aft-bulkhead area, limiting the stacks to 25 half-columns. In order to provide for a more efficient use of the Space Shuttle capabilities, the assumption is made that the OMS kit will not be required.

Package Configuration

A schematic side view of the packaging is shown on Fig. 38. Whenever possible, the column stacks should be oriented with the large end turned toward the cargo bay aft-bulkhead, since this position is favorable from a balance standpoint. The small canisters, which contain the node joints, are mounted on top of the half column container, where they can be used to provide some measure of c.g. trim.

Cross-sections through the Space Shuttle cargo bay are shown on Fig. 39-A and -B. Figure 39-A presents the configuration using the heavier half-columns (6.81 kg - 15 lb). In this case, 68 storage compartments are available for half column storage when the OMS kit is not on board. This configuration is comprised of 3,876 half columns and 433 node joints. As seen on Fig. 39, this arrangement is weight limited, leaving a significant unused volume. Unloading the payload and reloading empties may be facilitated by this available volume.

Figure 39-B presents an alternate configuration for the case of light half-columns (4.54 kg - 10 lb), where 100 stacks may be carried. The total number of half-columns necessary to match the maximum payload weight is 5,400 and the number of joint fittings, 600. Although there is little usable volume left, this configuration is also weight limited, but removal of the payload and reloading of empties does not appear to present undue difficulties.

Note that in order to achieve the 29,510 kg (65,000 lb) Space Shuttle payload limitations, only 54 half-columns per nest need be stacked in lieu of the maximum possible 57. It would be possible to package additional columns by changing the column geometry if additional mass capability was available.

6.4 LOAD MANIFEST FOR VARIOUS PAYLOAD OPTIONS

The following load breakdown is based on a maximum Space Shuttle payload of 29,510 kg (65,000 lb); light half-columns, 4.54 kg (10 lb) and heavy half-columns, 6.81 kg (15 lb) stored in the cargo bay with and without OMS kit. The pertinent data is tabulated following:

LOAD MANIFEST WITH OMS KIT

Half-Column Mass:	4.54 kg (10 lb)		6.81 kg (15 lb)	
No. half-columns	4,160		2,926	
No. node fittings	462		325	
Masses:				
OMS kit	6,472 kg	14,255 lb	6,472 kg	14,255 lb
Joints and canisters	668 kg	1,472 lb	470 kg	1,036 lb
Half-columns	18,886 kg	41,600 lb	19,926 kg	43,890 lb
Half-column canisters	1,589 kg	3,500 lb	745 kg	1,641 lb
Resupply (consumables)	726 kg	1,600 lb	726 kg	1,600 lb
Total	28,342 kg	62,427 lb	28,340 kg	62,422 lb
Gross contingency	1,168 kg	2,573 lb	1,170 kg	2,578 lb
Payload	29,510 kg	65,000 lb	29,510 kg	65,000 lb

LOAD MANIFEST WITHOUT OMS KIT

Half-Column Mass:	4.54 kg (10 lb)		6.81 kg (15 lb)	
No. half-columns	5,400		3,808	
No. node fittings	600		423	
Masses:				
Joints and canisters	866 kg	1,907 lb	611 kg	1,347 lb
Half-columns	24,516 kg	54,000 lb	25,932 kg	57,120 lb
Half-column canisters	2,274 kg	5,010 lb	1,071 kg	2,359 lb
Resupply (consumables)	686 kg	1,510 lb	726 kg	1,600 lb
Total	28,342 kg	62,427 lb	28,341 kg	62,426 lb
Gross contingency	1,168 kg	2,573 lb	1,169 kg	2,574 lb
Payload	29,510 kg	65,000 lb	29,510 kg	65,000 lb

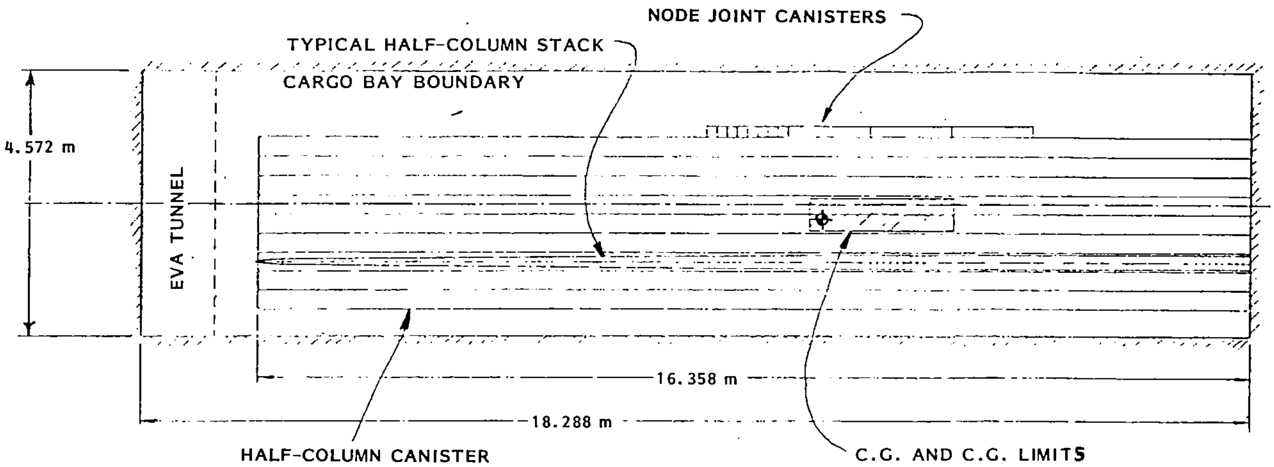


Figure 38. Packaging Configuration in Space Shuttle.

6.5 REMARKS

An examination of the load manifest in Section 6.4 shows that the operational efficiency of the Space Shuttle can be seriously degraded whenever extraneous duties are imposed on it. The energy requirements necesssary to meet these duties make it essential to carry an OMS kit, thereby reducing the payload capabilities by more than 20 percent (for each kit).

Use of the Space Shuttle itself as a base and as a tool for the purpose of assembling very large space structures is inefficient. It is, however, practical for constructing relatively small space hardware, such as the small area and linear platforms shown on Figs. 18 and 19.

The assembly of large space platforms using the Space Shuttle as the main assembly tool appears impractical for other reasons such as the increase in turnaround time, and the necessity of leaving the structure under construction idle while the Shuttle is on its 14-day resupply cycle, which considerably increases the assembly time.

A.

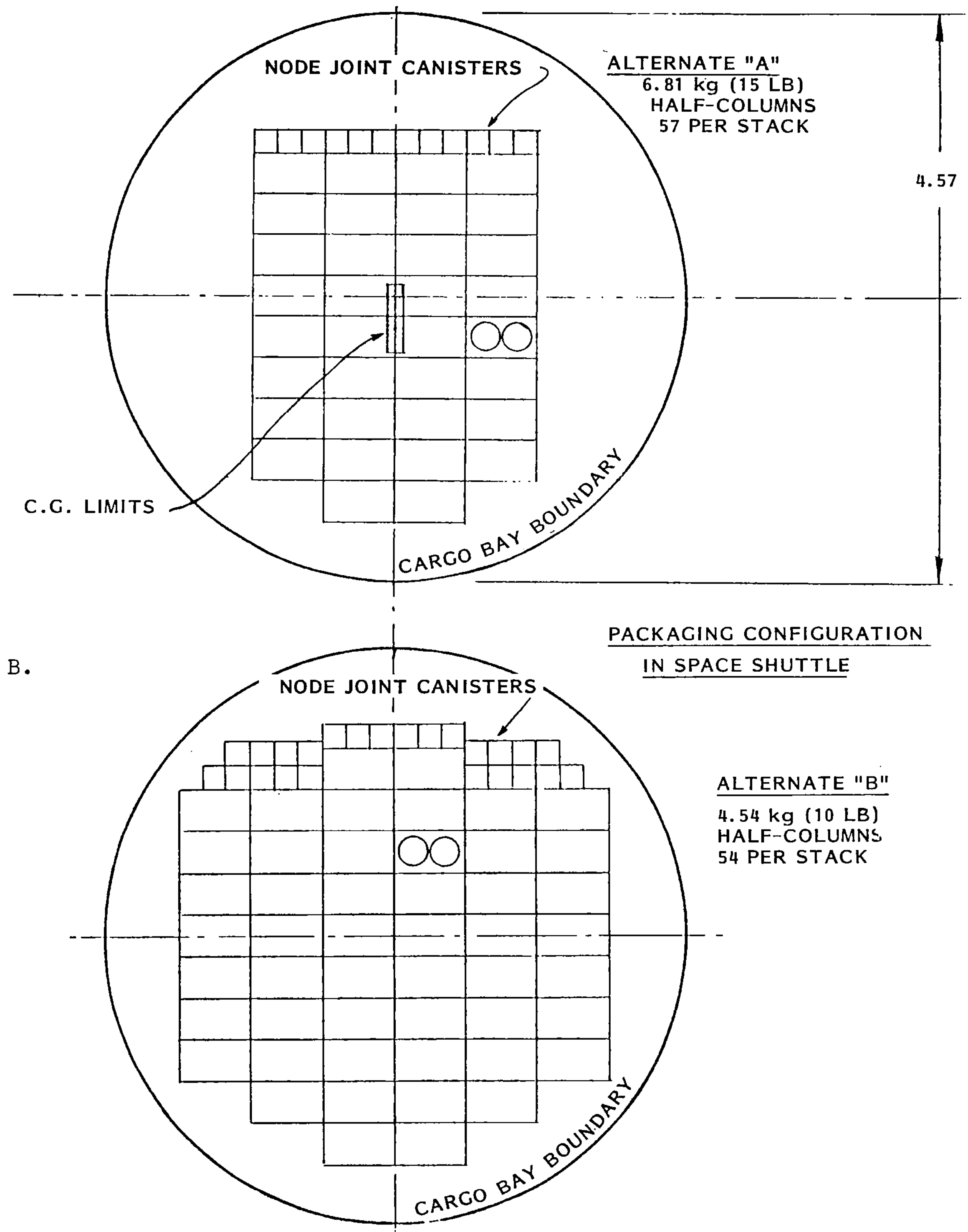


Figure 39. Packaging Configuration (Cross Section).

Section 7

SUMMARY OF CONSTRUCTION TIME ESTIMATES

7.1 INTRODUCTION

Detailed estimates of platform construction times for a Space Shuttle load of 2700 complete columns and 600 node joint fittings were computed for the gimballed parallelogram assembly described in Section 6.2. Estimates were also made for the rigid version of the parallelogram assembler and the tracked assembler described in Appendix A. These results are summarized in this Section, and estimates are made for the time required to construct larger platforms. Estimates have been made for the assemblers in the free flyer mode. No estimates have been made for the "Orbiter attached" concept although assembly times could be less than for the free flyer.

7.2 BASIC ASSUMPTIONS

In the absence of flight experience, the construction time estimates must be based on a set of assumptions. These assumptions, listed below, include those formulated in Sections 5.2 and Appendix A, where the basic operation times have been established.

- The Space Shuttle basic turn-around time is 14 days.
- The Space Shuttle is used only to carry supplies and return empties.
- All on-orbit equipment is power self-sufficient.
- Half-column assembly is performed on the assembler beams for the gimballed parallelogram concept.
- A separate machine is available to assemble the half-columns for the two assembler concepts discussed in Appendix A. For these versions, "Mini Tugs" are available to the astronauts for handling column canisters between the column assemblers and the assembly machines.
- For the assemblers requiring the remote assembly, an astronaut assisted construction time is computed on the basis of one 8-hour shift per day.

- For the gimballed parallelogram assembler platform, construction takes place while the Orbiter stays nearby, on orbit. Once the columns and node joints are off-loaded from the Orbiter to the assembler, construction is performed non stop to exhaustion of supplies.
- If the gimballed assembler is carried on the same flight as the columns and node joints, the number of columns that can be carried will be reduced. The number of columns that can be carried will depend upon the size of the column being assembled (5 m or 20 m) and the associated assembler.

7.3 BASIC CONSTRUCTION TIME PER NOMINAL SPACE SHUTTLE LOAD

This analysis was performed on the basis of a nominal Space Shuttle load of 2700 complete 20 m columns (5400 half-columns) and 600 joints. For this particular case, the following data are extracted or derived from Sections 5.2 and Appendix A for the parallelogram and tracked assemblies respectively.

Assembler		Gimballed Parallelogram	Rigid Parallelogram	Tracked
Traversing time	Hours	13.2	31	18
Column insertion	Hours	14.6	18.4	66
Machine reloading	Hours	8.0	24 to 48	6
Total	Hours	35.8	73.4 to 97.4	90
8-hour days		N/A	9.2 to 12.2	12.5

The nominal 2,700 column load corresponds to the erection of a platform measuring 578 m x 173 m, which consists of 9 rows of 33 traverses. Its area is 0.1 km^2. The total number of columns necessary to build a 1 km^2 platform would require 10 nominal Space Shuttle loads or 26,280 columns.

The gimballed parallelogram assembler is obviously the most efficient system. Once the assembler is loaded with a full cargo bay of column and joint

canisters, platform construction is continuous and construction is not broken down into 8 hour days.

The number of hours shown in the above table indicates that the rigid parallelogram and tracked versions require about 2 to 2 1/2 times the number of hours as the gimballed parallelogram assembler to construct a 2700 column platform. Additionally, the former two assembler concepts require periodic loading and astronaut assistance. The construction period is therefore limited to 8 hours per day for these concepts.

For the gimballed assembler, the canisters of columns and node joints are off-loaded from the Orbiter, and platform construction is completed within 36 hours. At that time the Orbiter is free for a return flight. The two other assembler concepts require approximately 12 days to construct a 2700 column platform. The column elements can be off-loaded onto a supply depot where the half-column assembly is performed. In this case the Orbiter will be required to stand by during assembly in order to provide crew servicing and support. The additional time required for maintaining the Orbiter on station and supporting the crew will necessarily require additional supplies and reduce the space in the cargo bay for column and node joint packaging.

7.4 CONSTRUCTION TIME FOR LARGE PLATFORMS

The time necessary to construct larger platforms, (i.e., those requiring more than one Shuttle load of columns, is determined by adding the fourteen day turn around time of the STS system in the case of the gimballed assembler. However, for the rigid parallelogram assembler or tracked assembler, the method of operation is changed and specific procedures must be selected. With more than one Shuttle load of columns required for construction a choice must be made whether to keep the Orbiter on station for the 12 day construction period, or off load the columns to an assembly depot and return the Orbiter for another load. In this latter case an on-orbit crew compartment must be provided, and payload space in the cargo bay will be reduced by the need to provide life support equipment and associated consumables. However, with the

12 day per load construction time being approximately equal to STS turn-around, continuous construction can be maintained.

The construction times estimated here for the rigid parallelogram and tracked assembler concepts are based on the assumption that it is more economical and less complex to provide the EVA support from the Orbiter rather than provide an on-orbit crew compartment on the assembler.

A timeline comparison for the assembly concepts is shown on Fig. 40. It can be seen that assembly of one shuttle load of 20 m columns takes 1.5 days, and construction of a 1 km^2 platform requires ten flights or a total of 141 days for the gimballed assembly concept. The rigid parallelogram and tracked concepts require 246 days for the 1 km^2 mission. In addition to the incremented time required using the latter concepts, a remote assembly facility and additional EVA support is required.

The on orbit time required for assembly is shown on Fig. 41. This figure reflects the economics associated with high speed assembly. Since only 1 1/2 days are required for the assembly of each load with the gimballed assembler, minimum time on orbit is required.

Time estimates for the rigid parallelogram and tracked assembler are optimistic. The requirements for extended time on orbit and associated astronaut support will undoubtedly reduce the payload capability, and extend the time for construction of a specific size platform.

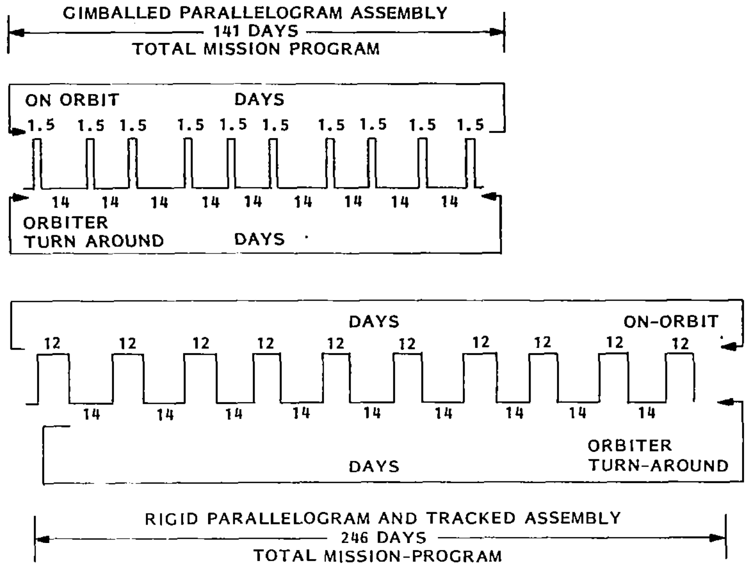


Figure 40. Program Timeline Comparison; Gimballed Parallelogram Versus Rigid Parallelogram and Tracked Assemblers.

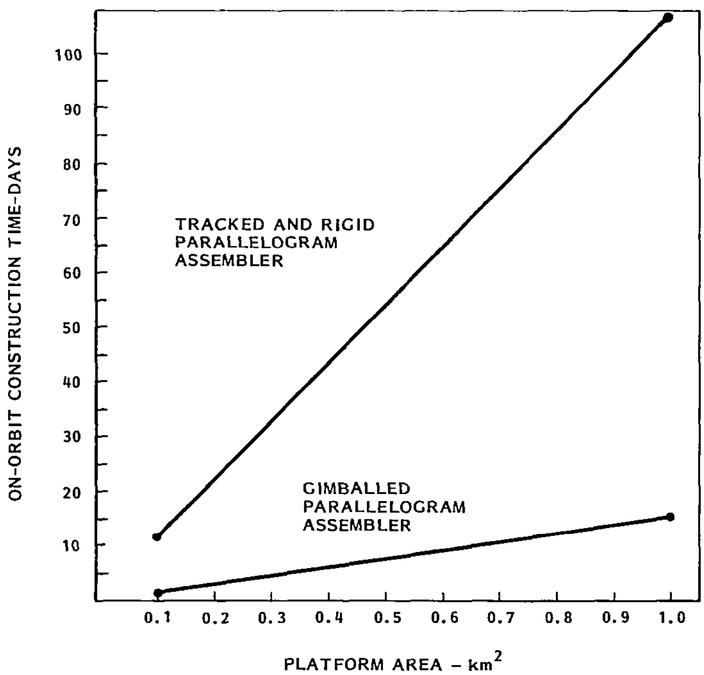


Figure 41. On Orbit Construction Time Comparison.

Section 8

CONTINUOUS ON-ORBIT OPERATION OF MECHANISMS

Continuous operation of mechanisms in the orbital environment is a new field of engineering which has received considerable attention in the past few years, but little actual flight experience. The majority of past applications are confined to the deployment of satellite appendages and the operation of relatively small equipment, such as cameras and tape recorders, solar arrays and antennas, orientation systems, and other mechanisms generally involving gearboxes and designed for sporadic use with long periods of inactivity. The majority of spacecraft mechanisms designed so far were intended for a single operation: deployment and locking of appendages to a fixed position on the spacecraft. The advent of the Space Shuttle, with its retrieve capability, adds a new dimension to these mechanisms, which must now become restowable.

In the design of the space platform assemblers, the complexity of the problem is increased by several orders of magnitude, as it will be necessary to operate sophisticated mechanisms almost continuously over several months at a time and with a reliability at least equal to or better than that which could be expected at sea-level.

The operation of mechanisms on-orbit must be performed in an environment which is characterized by:

- Zero-gravity
- Vacuum
- Lubrication problems
- Low reliability of some components (e.g., seals)
- Logistic problems of resupply, maintenance, and repairs
- Avoidance of contamination (outgassing of fluids and some critical materials)
- Lack of rigid bases to reference and maintain alignments
- Dynamic interactions among components

- Space Shuttle lift capability constraints which impose the use of large, light structures which cannot be made as rigid as their sea-level counterparts.

The major items in the above lists are briefly discussed below, in order to point out some of the considerations which must enter into the structural and mechanical design of the platform assemblers.

Zero Gravity

In a zero-gravity field, the only loads seen by a structure are those generated by the accelerations imposed on some moving components. These light loading conditions are conducive to the erection of lightly-built structures, which are necessarily very flexible by comparison with their sea-level counterparts. Therefore, the structural design of these platform assembly machines will be largely governed by dynamic response characteristics.

Mechanisms, unless of large dimensions, are not generally sensitive to zero gravity. By comparison with sea-level operations, some loading conditions are less severe. Other problems, such as lubrication, are discussed below.

Vacuum

The effects of vacuum provide significant constraints in the selection of some materials. Outgassing and contamination by volatile products is a serious problem. Vacuum applies very severe restrictions on our ability to maintain proper lubrication between moving components, but it has one advantage, as it virtually eliminates corrosion.

Lubrication Problems

Lubrication is by far the problem which is most difficult to solve for the reliable operation of these machines. Lubricated components may be roughly divided into two categories: 1) Self-contained closed boxes (such as gear

boxes), and 2) Open systems directly exposed to the environment (chain drives, hinges, etc.). These must be considered separately.

In the present state-of-the-art, only two types of lubricants have been used successfully; dry lubricants (MoS_2 is typical), and fluid or grease lubricants, based on Teflon in a silicone carrying fluid. Experience with dry lubricants indicates that they generally have a relatively short life. The best life is achieved with baked-on dry lubricant. However, replenishment is a problem which is difficult to solve in the on-orbit environment. Some compounds, such as Nylon/MoS_2 bearing materials, may offer satisfactory operation.

Fluid or grease lubricants are commonly used in sealed mechanisms, such as gear boxes, where they perform satisfactorily as long as there are no losses through worn or damaged shaft seals. Special disposition must be taken in these boxes to ensure that in zero-gravity, the lubricant does not collect on the internal walls, away from the bearings and gears.

The problems of lubricating open systems directly exposed to the environment remain to be solved for this new application.

Low Reliability of Some Components

On-orbit maintenance of continuously operating mechanisms will be difficult. It seems to be limited to replacement of fairly large components, which may be disabled by failure of small parts. Some of the most troublesome small parts are the seals, which cannot be expected to have a very long life when exposed to vacuum on one side.

This will make it necessary to examine the behavior of such components closely through long duration tests in a simulated environment.

Logistic Problems of Resupply, Maintenance, and Repairs

Any unscheduled work stoppage caused by mechanical or other failure in the assembler may have very costly consequences as it would force unacceptable delays in the whole operation. These problems must be addressed very carefully in order to incorporate features in the design such that any stoppage can be remedied rapidly. Supplies of easily replaceable components must be available on-orbit so that repairs can be carried out in short order without having to wait for the next Space Shuttle flight.

Avoidance of Contamination

There are two major causes of contamination; outgassing and fluid leakages. Outgassing is a well understood problem which need not be elaborated on here. The avoidance of leakages depends on the reliability of seals. In general, rotary seals around shafts have a longer life than sliding seals, such as those of hydraulic actuators and dampers. In all cases, the performance of a seal depends on some lubrication in the area of contact. On rotary seals, the inner lip is always in contact with the fluid while the outer lip is exposed to vacuum. Migration of fluid toward vacuum is minimized in this case, since there is no axial motion through the seal. In the case of push rod seals, it is extremely difficult to avoid a certain amount of wetness of the shaft as it exits from the seal. If it was possible to have the shaft come out perfectly dry, it would, in time, tear up the elastomer, thus ruining the seal. In some applications, even the small amount of fluid lost through a good axial seal has been found objectionable for the operation of nearby sensitive equipment.

For this reason, it has been considered inadvisable to make use of any hydraulic systems in the conceptual design of these platform assembly machines. Pneumatic systems, which had been considered at the initial stage of the study, were also dropped because of the gas supply requirements, which has a detrimental effect on the Space Shuttle transport efficiency. An all-electric system appears to be the best alternative.

Lack of Rigid Bases to Reference and Maintain Alignments

In considering the construction method of the structure of the platform assembly machine, it became apparent that some means of verifying alignments will be needed. Since these machines are effectively very large construction jigs, they must be adjusted within specified tolerances. This adjustment should be verified periodically to prevent difficulties in assembling the platform.

At this stage of the conceptual study, a technique has not been defined to perform this task. It is desirable to establish an element of the structure which can be rigid enough to provide a basic reference from which the position of the specified points may be measured. In view of the unavoidable flexibility of the contemplated framework, it is believed that one possible technique may be through the use of laser beams reflected by mirrors to strike receivers at the reference points. Such a system could conceivably be coupled through the on-board computer to provide frequent periodic checks.

Dynamic Interactions Among Components

The operation of the platform assemblers requires many functions which will create transient accelerations (either start or stop). Since the structure cannot be made extremely rigid, deflections may be significant enough to induce detrimental misalignments, or to require waiting for subsidence of lightly damped oscillations, before proceeding with the next motion. The solution of this problem will require analytical as well as experimental studies. It may be possible in some cases to introduce some measure of control via a laser beam monitoring system, as suggested in the preceding paragraph.

Section 9
ENERGY SOURCE SELECTION

Although this conceptual study is not advanced enough to quantitatively define the energy requirements of such an operation, enough information is available to give a brief qualitative description.

Note that, throughout this report, electric power was considered exclusively, in preference to any other source of energy. This selection was made:

a. To remove any source of contamination

b. To reserve the Space Shuttle lifting capability exclusively for construction material supplies

c. For in-situ availability of electric power from large solar array technology spacecraft and from solar arrays mounted directly onto the platform assemblers

d. For higher operating efficiency

In addition to the electrical energy requirements, compressed gas power will be required for astronaut transportation and operating mini-tugs and other handling equipment.

Hydraulic Power

Hydraulic power presents several disadvantages in addition to the risks of contamination through fluid leakage.

a. It does not eliminate the electrical power requirements, since pumps must be driven electrically.

b. Since the creation of hydraulic energy requires one extra step, a loss of efficiency must be accounted for, as it increases the electrical power requirements.

c. Hydraulic fluids are notoriously sensitive to temperature changes. It would therefore be necessary to insulate and perhaps provide additional heat to those components operating in the shade. Furthermore, the hydraulic system may have to operate with components at various temperatures, i.e., with fluid of varying viscosity. All this translates into additional efficiency losses which must be made up by further increment on the electrical power demand.

Pneumatic Power

The major disadvantage in the operation of a pneumatic power system in vacuum is the difficulty of resupplying the power medium from the environment. Supplies of compressed gas would be brought up by the Space Shuttle, packaged in heavy bottles thus reducing the Space Shuttle operational efficiency. Other problems exist in the reliability of actuator seals operating unlubricated between vacuum on one side and a dry gas on the other side.

Electrical Energy

In view of the disadvantages discussed above for hydraulic and pneumatic power, the direct use of electrical energy is justified, especially since the state-of-the-art is well developed and backed by considerable flight experience.

The general concept envisions the use of solar arrays mounted on the platform assembler. It is recognized, however, that the assembly machine may not be able to carry a very large array because of dynamic interraction problems between the machine and the large flexible structure of the array. This problem may place a limit to the array size which could be below that required for self-support. It may be possible to obtain all or additional energy from

an energy collecting spacecraft, such as the 25 kW Power Module, parked nearby. However, the problem of transporting the energy from the power module to the assembler is still to be addressed. The use of an umbilical cord does not appear practical because of the long distances which the machine must travel and the risks of snagging from all the activities surrounding the site. Wireless transmission offers a method of solution but this consideration requires a specialized study which is beyond the scope of this report.

Section 10

CONCLUSIONS AND RECOMMENDATIONS

This study shows that automated assembly systems are capable of performing all of the functions necessary to erect tetrahedral truss platforms. The time required to erect a 1 km^2 structure from 20 meter columns can be 141 days. The most important time factor in the assembly is time required to deliver the hardware to orbit. It also appears that Shuttle cost on-orbit, and the associated decrease in payload efficiency for extended times, emphasizes a minimum orbit duration for the Orbiter. Construction of a 0.1 km^2 platform can be accomplished in 36 hours.

A study of the type reported here often raises more questions than it answers. An effort was made to integrate the study from cargo bay to completed structure. However, a number of assumptions were made to evaluate the overall feasibility of the assembly concept. Experimental (in some cases analytical) verification or modification of these assumptions is required to more precisely define the assembly process. Additionally, as discussed throughout the report, better definition or trade studies are required. As each of these is performed, a valid integrated study becomes more feasible. Among these are the following.

a. A better definition of astronaut capability in EVA is required to determine requirements for presenting tasks to the astronaut, and more precisely defining the time of assembly.

b. Associated with (a) is a definition of crew requirements on-orbit.

c. A study of the dynamics and control requirements of assembly. Included here is a trade study between canister size and assembler dynamics for the gimballed parallelogram type assembler.

d. Detailed definition of the power requirements associated with automated assembly. Specifically, it should be determined whether the assembler can carry a power system sizeable enough to make it self-sufficient.

e. Tradeoff between mechanical and software complexity and logistics problems associated with one standardized type handling and insertion device versus several simplified insertion mechanisms.

f. Although the concept of constructing smaller platforms from the Orbiter was defined, no time lines were established. A need exists to define the platform sizes that can economically be constructed from the Orbiter, with special emphasis on the dynamic interaction issue.

APPENDIX A

ASSEMBLER PRELIMINARY CONCEPTUAL STUDIES

This appendix presents the results of previous conceptual studies which generated two different types of Platform Assemblers. The machine described in Section 5 is their descendant, and incorporates many mechanisms which are shown in this appendix.

Two automated methods of erecting a tetrahedral truss structure were evaluated. A rigid moving parallelogram forms the basis for one system, and a continuous tracked rigid structure is the basis for the other. Both systems are designed to be fully automatic, with EVA back-up.

Two half-column concepts were examined (individually nested and hinged) and two joint concepts (directional access and random lateral access) were evaluated.

The following table displays the matrix of possible concept combinations considered.

Matrix of Assembly Evaluation

	Rigid Parallelogram Fixture	Tracked Fixture
Column Concept/ Joint Access	Directional Individual/Random	Hinged/Directional

A1-1 RIGID PARALLELOGRAM ASSEMBLER, DESCRIPTION, AND KINEMATICS OF OPERATION

The concept of this fixture is shown on Fig. A-1. The node retainers, which have the purpose of gripping the truss at the nodes, are shown in their extended position. For smaller platforms requiring only a single docking of the Orbiter, a crew compartment is not needed (Sec 6.2.8).

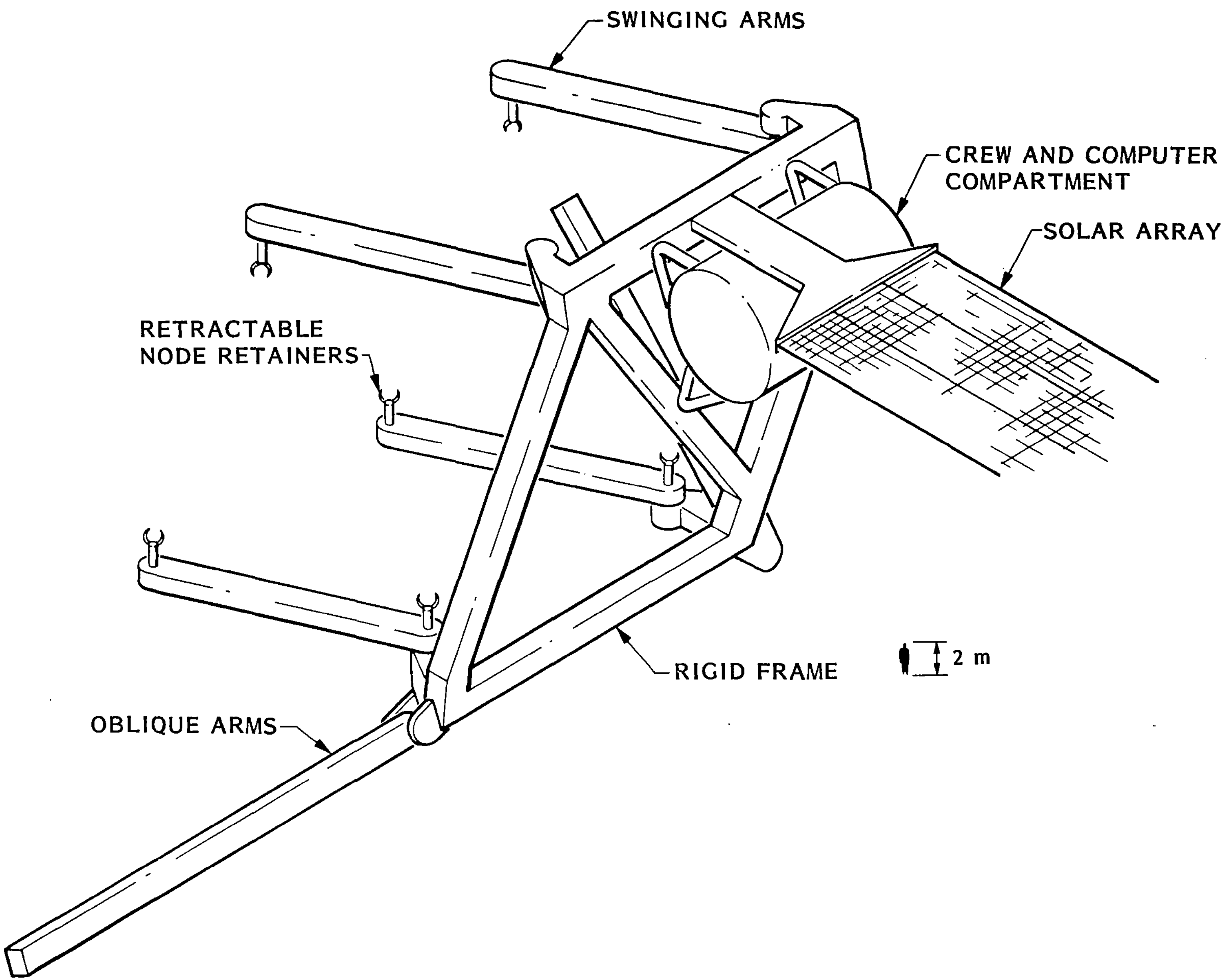


Figure A-1. Concept of Rigid Parallelogram Assembler.

Definitions

The following terms are defined to prevent misinterpretation:

Traverse. Crab-like lateral displacement of the assembler along the edge of the platform under construction.

Right Hand Traverse. Traverse moving toward the right hand, as viewed on the drawings.

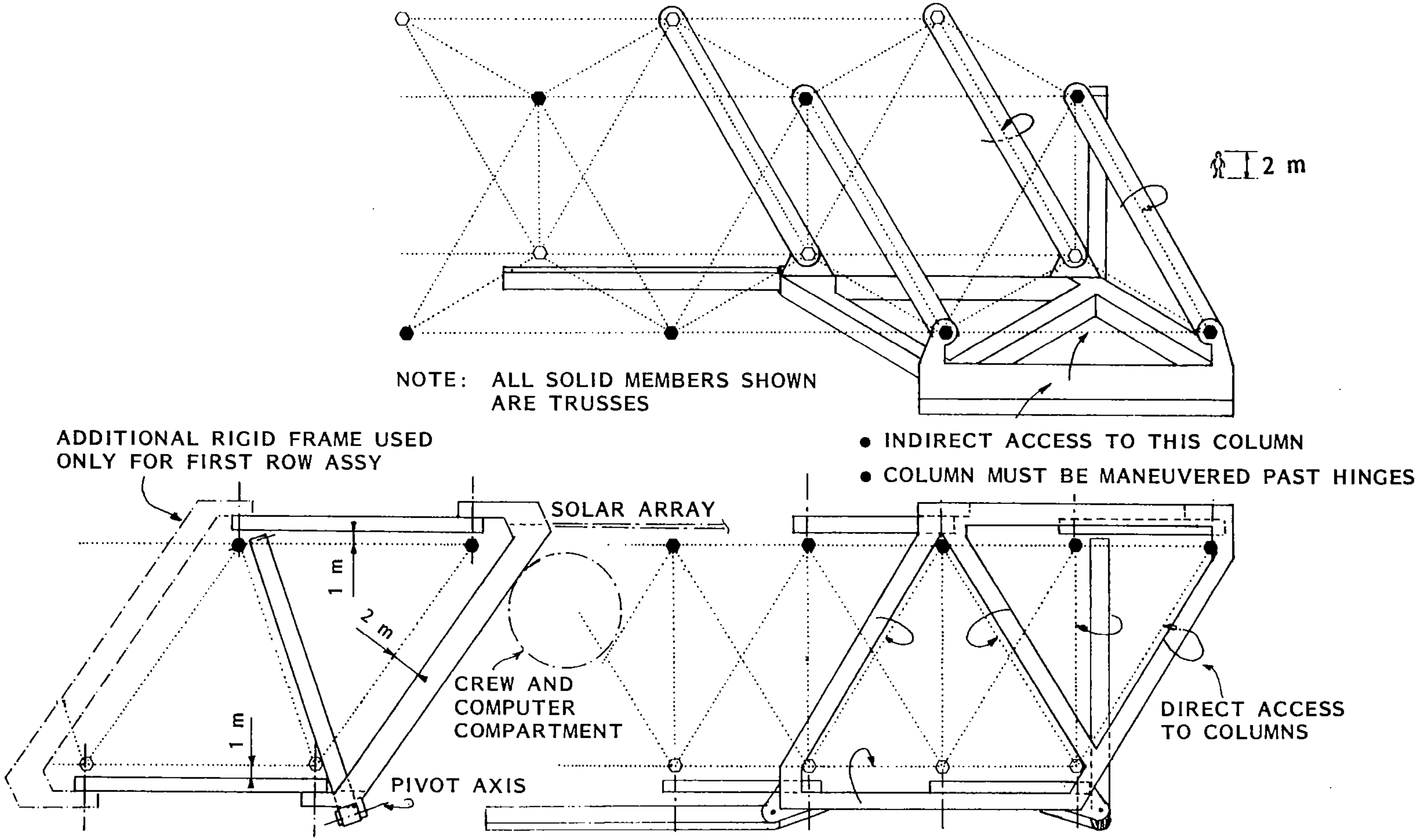
Left Hand Traverse. Traverse moving toward the left hand, as viewed on the drawings.

A1-2 DESCRIPTION OF PROPOSED ASSEMBLER

Schematic of General Layout

The general layout of the assembler is shown on Fig. A-2 in a schematic form. All solid members shown in this layout are effectively trusses built up from deployable structural members made from graphite epoxy. This machine must be assembled on-orbit from the Space Shuttle cargo bay by means of special equipment and EVAs. Its main features and objectives are as follows:

- It is capable of assembling the first row of a space frame, which requires the installation of 15 columns for the first element and 10 for the subsequent ones.
- It is capable of moving sideways, either right or left, and backward, to change rows as the assembly progresses.
- Its operation, under computer control, is as completely automatic as possible, requiring astronaut assistance only in case of difficulties.



NOTE: • NODE RETAINERS MUST BE RETRACTABLE -
• NODE ROTATION MUST BE CONTROLLABLE AND HAVE FREE-WHEELING CAPABILITY

Figure A-2. General Layout of Rigid Assembler.

- All functions are performed electrically (DC or stepper motors) and ORU. All working units are easily removable for replacement and repairs.

- Platform erection time is such that all available supplies of nodes and columns are exhausted within one Space Shuttle flight cycle.

- The half-column (10 meter) assembly into full columns (20 meter) is performed either independently of the assembler, which receives stacks of columns at specified locations selected for convenient handling by the insertion mechanism, or the columns are assembled directly on the assembler.

- Positioning of the columns into the structure must be performed by a mechanism having the simplest motion consistent with precision locating requirements.

- Node installation in the fixture must be automatic.

- Fixture node retainers must be retractable inside the swinging arms and must provide controlled powered rotation to properly orient the nodes, as well as freewheeling during assembler motion.

A1-3 ASSEMBLER MOTION KINEMATICS

The general motion of the assembler is shown step-by-step for lateral traverse, change of row, and first row construction. A simplified schematic representation is used to show the sequence of motions which must be performed to translate from one element to the next while installing each column. The lateral traverse is discussed first, as it is the simplest motion to be performed.

Right Hand Traverse

The assembler configuration moving to the right (right hand traverse) is shown step-by-step on Fig. A-3. The initial configuration, shown on Fig. A-3A, has the moving arms slanted to the right. Another alternate would be with the moving arms slanted to the left. In either case, the motion steps are identical, since Step 3 (Fig. A-3C) corresponds to the second alternate.

On Fig. A-3A, nodes N1 and N2 are set up in the machine and all columns except C1 and C6 are inserted and locked in place.

On Fig. A-3B, nodes N1, N2, N1, and N2 are disconnected and the corresponding node retainers are retracted. Nodes N3, N4, N3, and N4 are set in the free wheeling mode and the assembly is swung about these four nodes as shown, to be reconnected at nodes N1 and N2.

On Fig. A-3C, after reconnecting at nodes N1 and N2, columns C1 and C6 are installed, and new nodes are inserted into the retainers at positions N1 and N2.

It is now necessary to rotate arms B1, B3, B2, and B4 clockwise, to restore the initial position of the assembler (as on Fig. A-3A). This is accomplished in two steps, which are shown on Figs. A-3 (D and E). In order to prevent any instability of the assembler/platform combination, only two nodes are disconnected at one time. The first step consists of swinging the upper arms, B1 and B3, to the next nodes, N3 and N3 (Fig. A-3D). After securing these nodes, the lower arms, B2 and B4, are disconnected from nodes N3 and N4 and swung over to nodes N3 and N4 (Fig. A-3E). The assembly is now ready to repeat the cycle and can proceed to the end of the row.

Note that the end of the row will require only a partial step, ending at the configuration shown on Fig. A-3C for the particular row treated in this demonstration. A different partial step is performed if the row ends at the position of Fig. A-3E to insert columns C1 and C6, or for restart capability at this point.

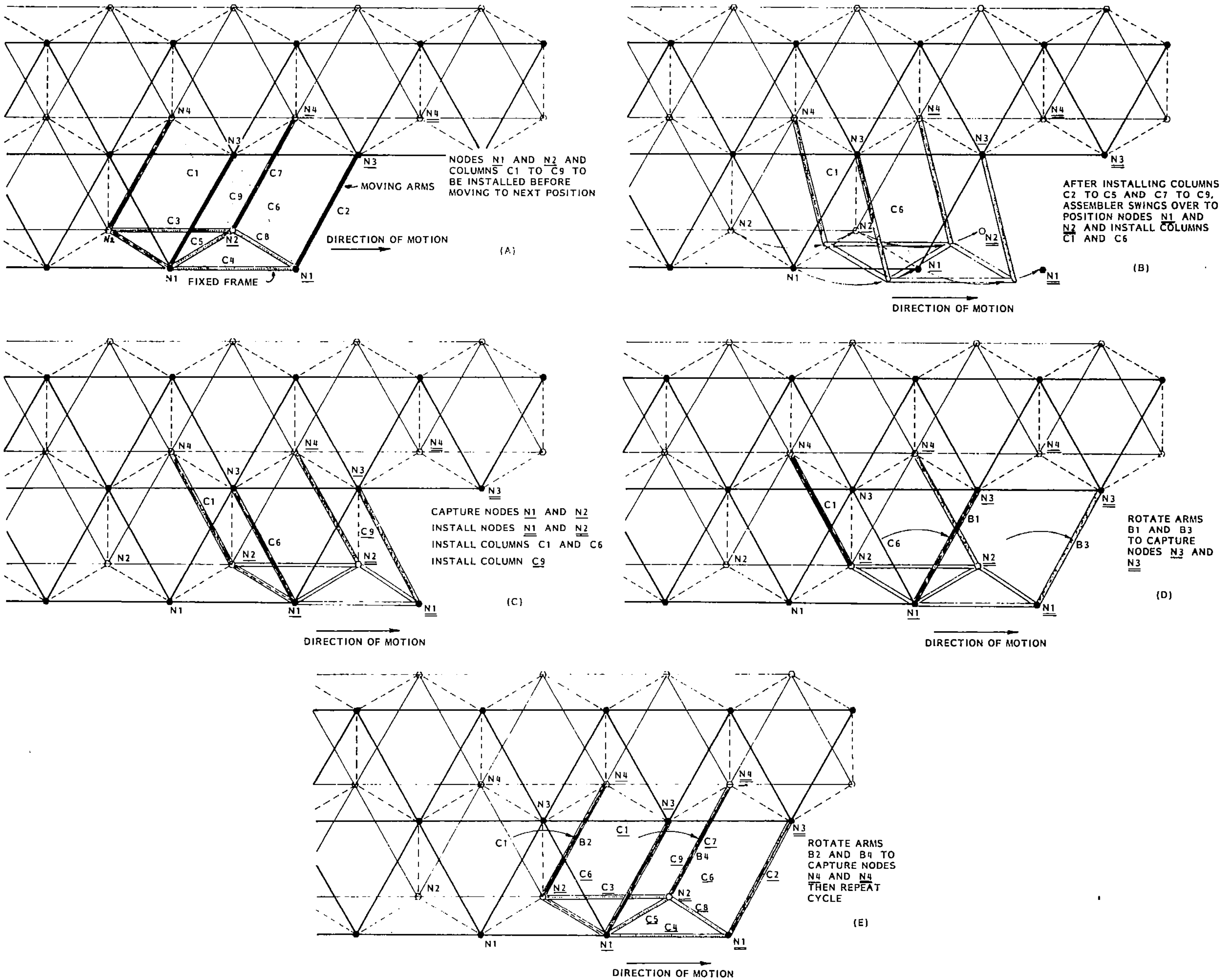


Figure A-3. Right Hand Traverse.

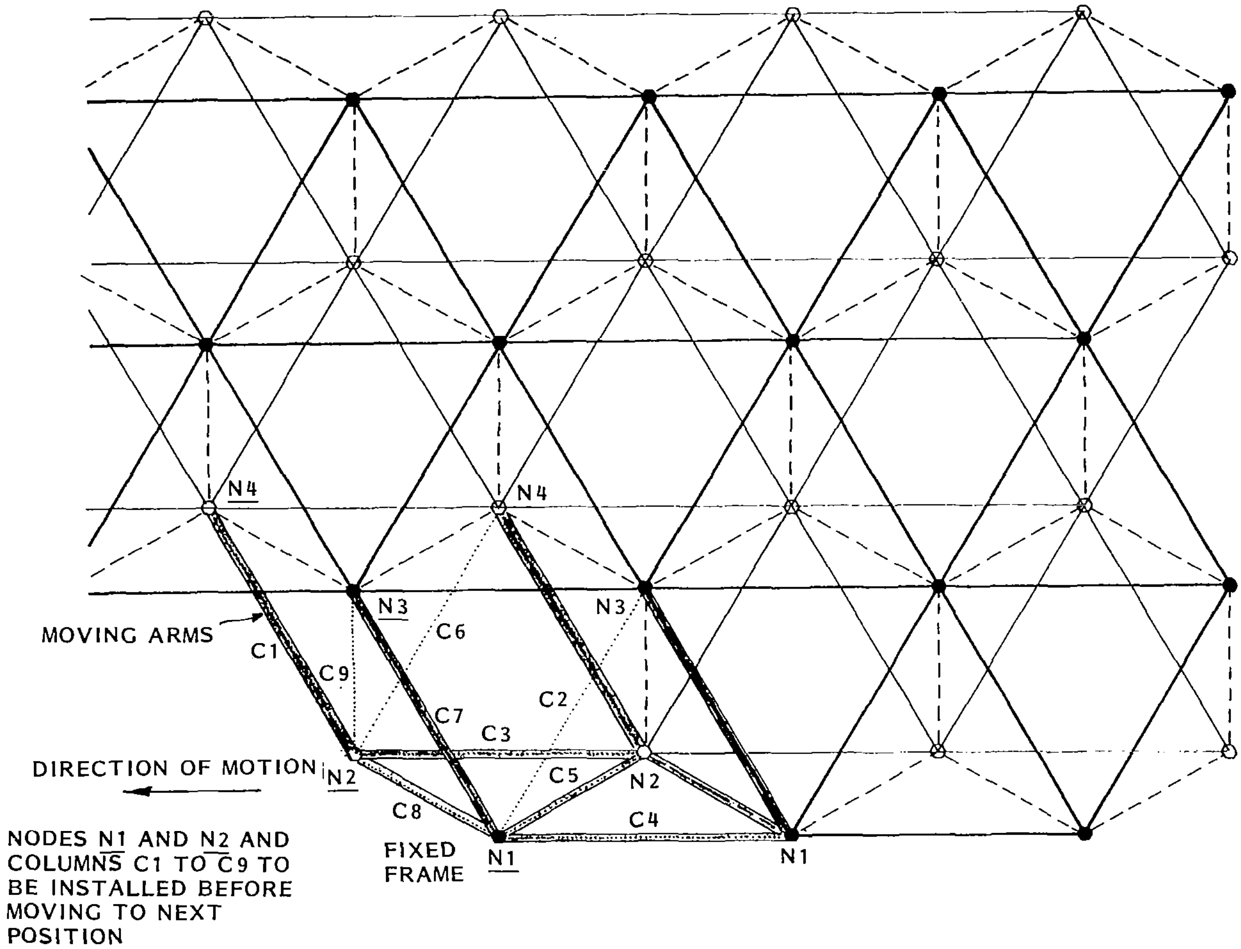


Figure A-4. Left Hand Traverse.

Left Hand Traverse

The procedure required to traverse toward the left is essentially the same as that described for the right hand traverse, by interchanging the directions of rotation. The basic initial configuration at the beginning of the cycle is shown on Fig. A-4. The steps necessary to perform one cycle of this traverse can be derived directly from the description of the right hand traverse, Fig. A-3.

Row Change

After completion of one traverse, the assembler must be reset at the start of the next row. The pertinent initial conditions at the end of a right hand traverse are shown on Fig. A-5A, where the dotted lines indicate the first elements of the following row. The rigid frame of the machine must be moved from the N nodes to the N nodes.

In defining the steps required to perform this translation, care has been taken to avoid applying detrimental loading to the platform nodes. In particular, torque should not be applied in the plane of the upper or lower frame surfaces (i.e., torques about axis normal to the surfaces), since the structure is primarily designed as a truss with flexible members. Special attention has also been paid to preserving the structural stability of the system, by disconnecting at any time the minimum number of nodes from the machine. With these considerations in mind, the following procedure provides the necessary translation and construction of the first two elements of the next row.

STEP 1. In this step, arms B1 and B2 are disconnected from their free end nodes and swung over to be reconnected at nodes N3 and N4 respectively. This is described pictorially on Fig. A-5B.

STEP 2. As in Step 1, arms B3 and B4 are disconnected and swung over to be reconnected to nodes N1 and N2. However, as the rigid frame is already connected at these two points, it must be disconnected, its hinges locked, and the two node retainers retracted. Since arms B3 and B4 cannot reach under arms B1 and B2, they are equipped with special offset retractable node retainers, designed to maintain an appropriate clearance, as shown on Figs. A-5C and A-5D. On the Fig. A-5D configuration, the electric drive between the rigid frame and arms B1 and B2 is locked rigidly to prevent any unwanted motion relative to the space frame. In this configuration, the rigid frame is ready to be swung downward toward node positions N1, N2, N3, and N4.

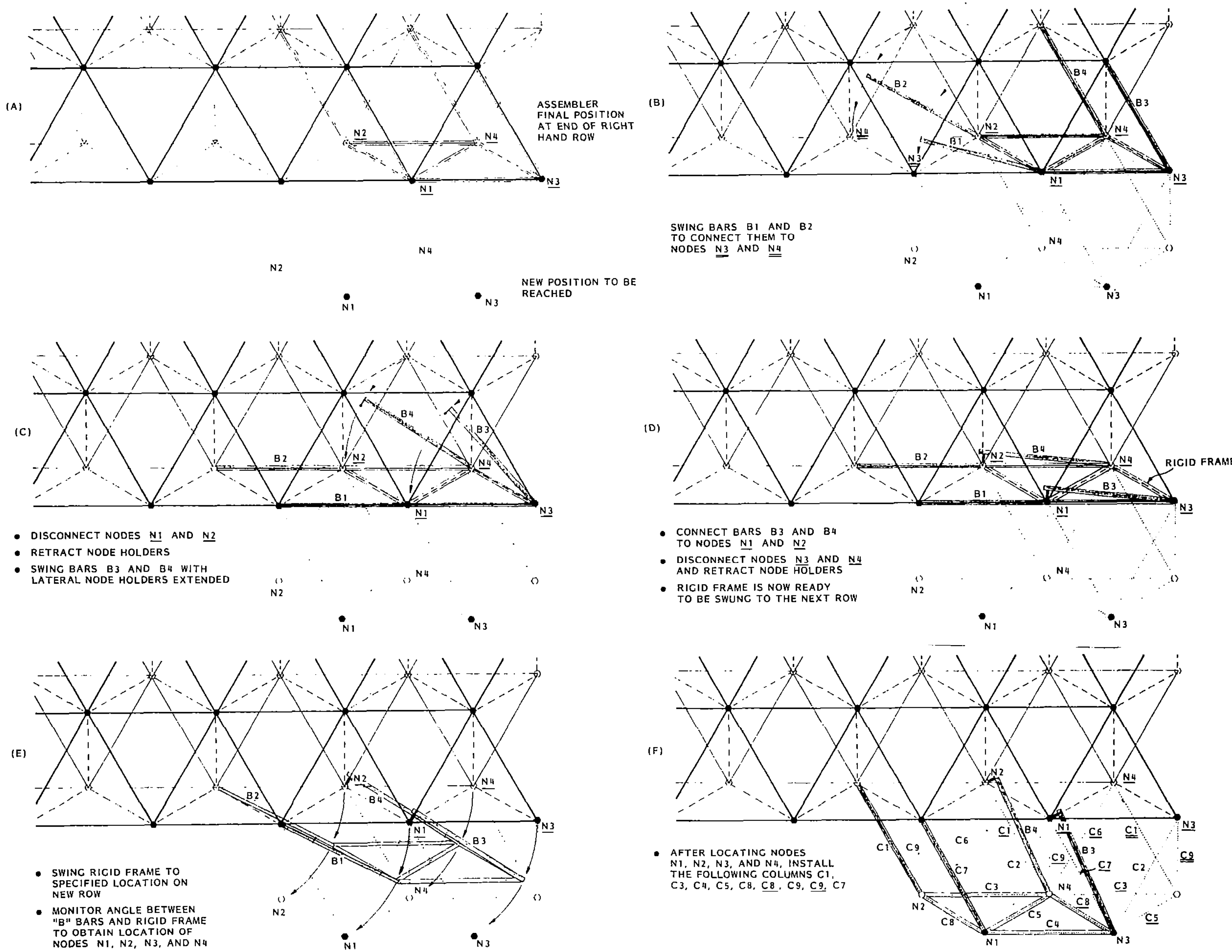


Figure A-5. Assembler Row Change.

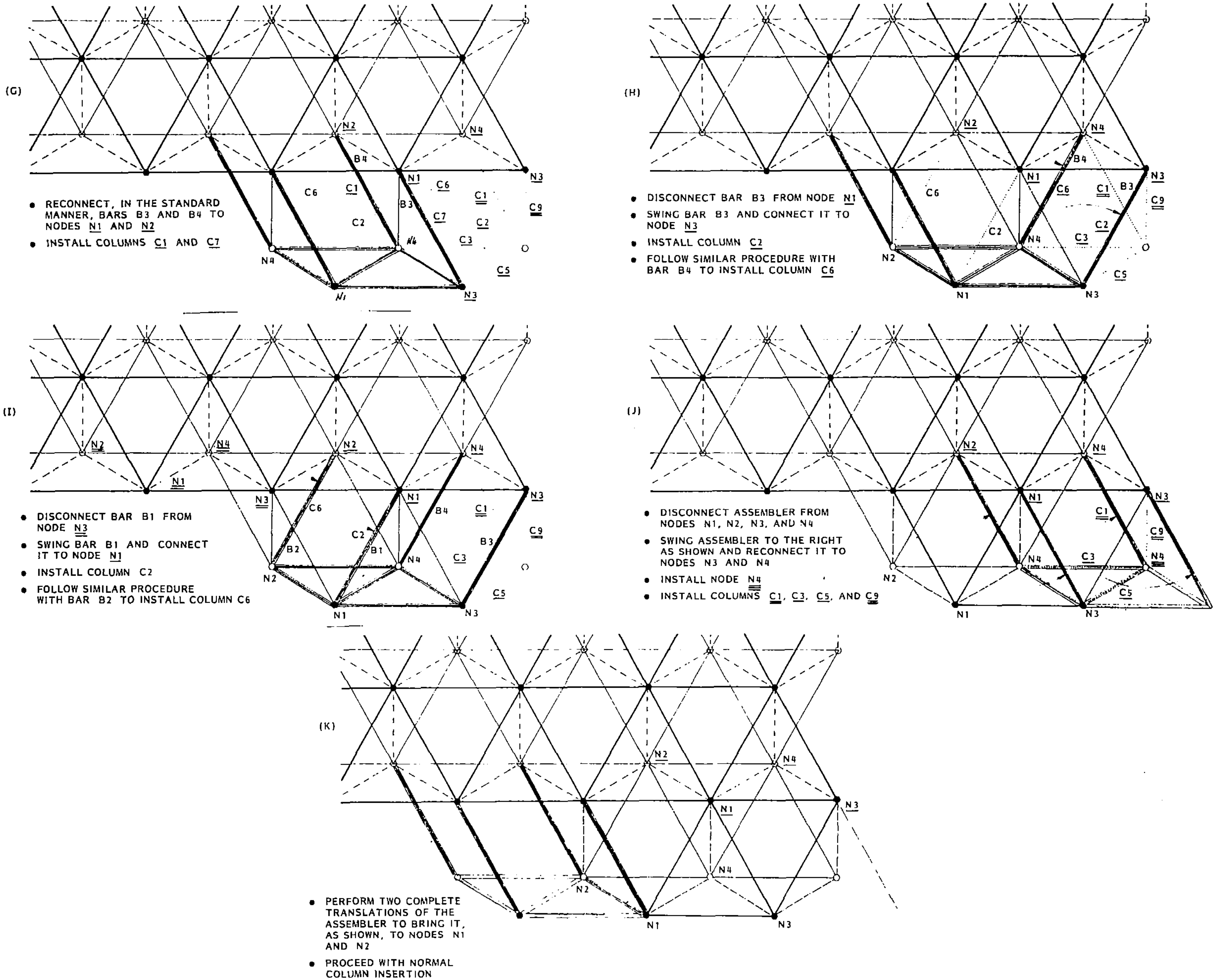


Figure A-5. Assembler Row Change (Concluded).

STEP 3. In this step (Fig. A-5E), the hinges electric drives are activated to swing the rigid frame toward node positions N1, N2, N3, and N4. The appropriate location may be obtained by monitoring the angle of one of the arms with respect to the rigid frame. Fine tuning can be obtained when inserting column C9. After inserting the four nodes in the fixture, the following columns can be installed: C1, C3, C4, C5, C7, C8, $\underline{C8}$, C9, and $\underline{C9}$ (Fig. A-5F).

STEP 4. In order to insert columns $\underline{C1}$ and $\underline{C7}$, the two corresponding arms B4 and B3 offset node retainers must be disconnected and retracted and the arms reconnected in the usual manner. At this stage, however, the assembly is incomplete and would become instable if both arms were disconnected simultaneously. Therefore, it is important to perform this operation one arm at a time. Columns $\underline{C1}$ and $\underline{C7}$ are inserted during this step (Fig. A-5G).

STEP 5. This step involves another rotation of arms B3 and B4, connecting them respectively to nodes $\underline{N3}$ and $\underline{N4}$, permitting the installation of columns $\underline{C2}$ and $\underline{C6}$, as shown on Fig. A-5H. Note that at the end of Step 4, the incomplete structure is still unstable if these two arms (B3 and B4) are disconnected simultaneously. Here again, it is important to perform this operation one arm at a time.

STEP 6. Arms B1 and B2 must now be disconnected from nodes $\underline{\underline{N3}}$ and $\underline{\underline{N4}}$ and connected to nodes $\underline{N1}$ and $\underline{N2}$, in order to insert columns C2 and C6 (Fig. A-5I). In this case, the structure is stable and there are no restrictions to the rotation of the arms.

STEP 7. Note that on Fig. A-5I, one node and four columns are needed to complete the end of the row. The fixture is swung to the right, as shown on Fig. A-5J, to locate node $\underline{\underline{\underline{N4}}}$ and insert columns $\underline{C1}$, $\underline{C3}$, $\underline{C5}$, and $\underline{\underline{C9}}$, thereby completing the assembly of this section.

STEP 8. In this step, the assembler starts the left hand traverse by two complete translation cycles, which reconnect its right hand side at nodes N1 and N2 (Fig. A-5K). Normal insertion can then proceed as described for the left hand traverse, until the left hand end of the row is reached, where a symmetric row change is performed, followed by right hand traverse. This process is repeated to completion of the platform.

First Row Assembly

The assembly of the first row presents some special considerations. In all other modes of assembly discussed previously, the assembler was working along an existing framework, which it expanded row by row. In order to start the assembly, it is necessary to construct a strut, which requires additional columns equivalent to the members represented by another rigid frame (Fig. A-6A).

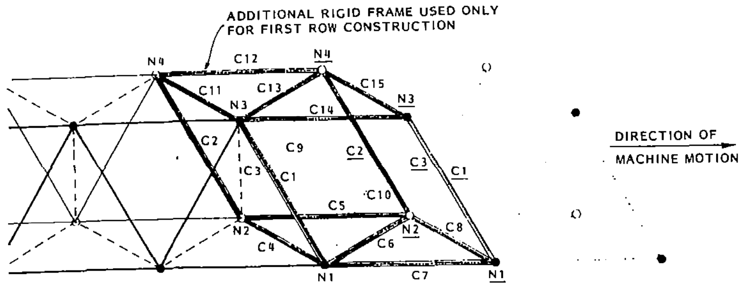
The concept of this assembler can be extended readily to cover this fabrication case. The method by which this is accomplished consists of temporarily adding another rigid frame to the assembler. This is shown on Fig. A-6A, where the additional fixture is located to connect with nodes N3, N4, $\underline{\text{N3}}$, and $\underline{\text{N4}}$.

With this fixture added, construction of the first row proceeds in a manner similar to that described for either right hand or left hand traverses. The sequence of operations required to construct the first row is then as follows in the case of a right hand traverse.

STEP 1. The additional fixture is disconnected from nodes N3, N4, $\underline{\text{N3}}$, $\underline{\text{N4}}$. It is swung clockwise (Fig. A-6B) to be reconnected at nodes $\underline{\text{N3}}$ and $\underline{\text{N4}}$.

STEP 2. With the additional fixture secured at nodes $\underline{\text{N3}}$ and $\underline{\text{N4}}$, new nodes are inserted in the retainers at $\underline{\underline{\text{N3}}}$ and $\underline{\underline{\text{N4}}}$. The following columns are inserted at this step: C9, $\underline{\text{C9}}$, C10, $\underline{\text{C10}}$, $\underline{\text{C12}}$, $\underline{\text{C13}}$, $\underline{\text{C14}}$, and $\underline{\text{C15}}$ (Fig. A-6C).

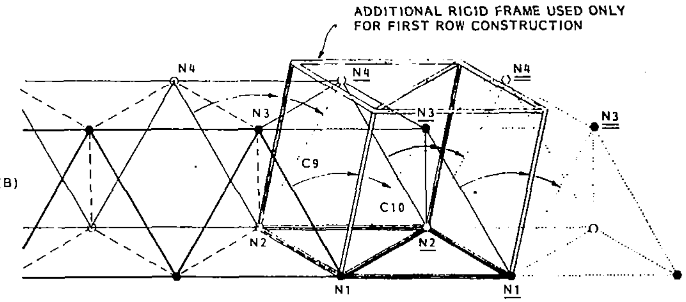
(A)



- IF MACHINE IS SETTING FIRST ELEMENT, INSTALL COLUMNS C1, C2, C3, C4, AND C11
- IF MACHINE IS SETTING AN ELEMENT AS SHOWN, INSTALL COLUMNS C5, C6, C7, C8, C1, C2, C3, C12, C13, C14, and C15
- COLUMNS C9 and C10 WILL BE INSTALLED IN NEXT SEQUENCE.

SEQUENCE NO. 1

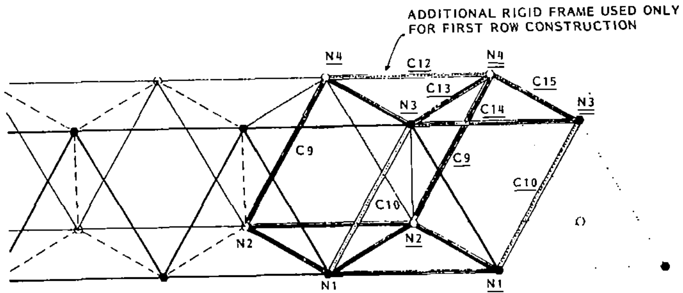
(B)



- DISCONNECT FRAME FROM NODES N3, N4, N3 and N4
- SWING ASSEMBLER CLOCKWISE TO RECONNECT AT NODES N3 and N4
- INSTALL NEW NODES AT N3, AND N4

SEQUENCE NO. 2

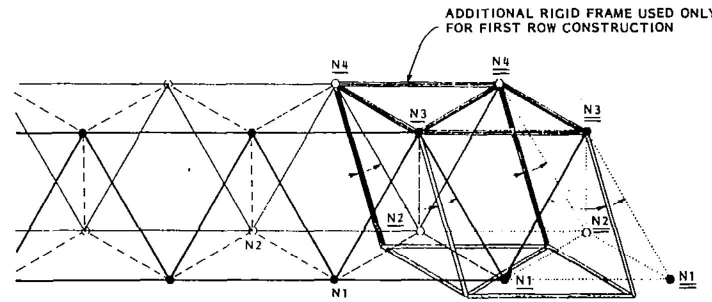
(C)



- ASSEMBLER LOCKED IN PLACE AS SHOWN
- INSTALL COLUMNS C9 and C10, C9, C10, C12, C13, C14, C15

SEQUENCE NO. 3

(D)

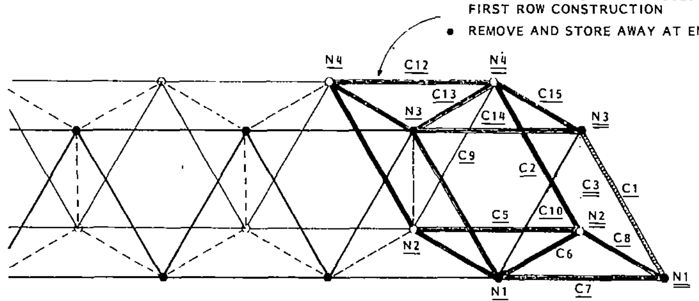


- DISCONNECT ASSEMBLER FROM NODES N1, N2, N1 AND N2
- SWING ASSEMBLER COUNTERCLOCKWISE, AS SHOWN, AND RECONNECT AT NODES N1 AND N2
- INSTALL NEW NODES AT N1 AND N2

SEQUENCE NO. 4

- ADDITIONAL RIGID FRAME USED ONLY FOR FIRST ROW CONSTRUCTION
- REMOVE AND STORE AWAY AT END OF ROW

(E)



- ASSEMBLER LOCKED IN PLACE AS SHOWN
- REPEAT CYCLE FROM SEQUENCE NUMBER 1 INSTALL COLUMNS C5, C6, C7, C8, C1, C2, C3
- CONTINUE ASSEMBLY TO END OF STRUCTURE
- REMOVE ADDITIONAL ASSEMBLER RIGID FRAME PRIOR TO MOVING TO NEXT ROW.

SEQUENCE NO. 5

Figure A-6. First Row Assembly.

STEP 3. In this step, the assembler is disconnected from nodes N1, N2, $\underline{\text{N1}}$, and $\underline{\text{N2}}$, to be swung about nodes $\underline{\text{N3}}$, $\underline{\text{N4}}$, $\underline{\underline{\text{N3}}}$, and $\underline{\underline{\text{N4}}}$, and reconnected to nodes $\underline{\text{N1}}$, $\underline{\text{N2}}$, $\underline{\underline{\text{N1}}}$, and $\underline{\underline{\text{N2}}}$ (Fig. A-6D).

STEP 4. Figure A-6E shows the end of the translation cycle where the following columns are inserted: $\underline{\text{C5}}$, $\underline{\text{C6}}$, $\underline{\text{C7}}$, $\underline{\text{C8}}$, $\underline{\underline{\text{C1}}}$, $\underline{\underline{\text{C2}}}$, $\underline{\underline{\text{C3}}}$.

Remarks About First Row Assembly

For reasons of stability, a limit must be placed on the length of strut which can be safely constructed. Therefore, when erecting a very large platform, it will be necessary to consider first assembling a square or a rectangle of relatively modest dimensions, then expanding it by starting the first row again. In this case, the additional rigid fixture should be disconnected from the assembler and left attached to the structure at the desired starting point. After having completed a section of the platform, the assembler could be brought back to this predetermined starting point, reconnected with the additional fixture to extend the first row for another section of the platform, and proceed with the assembly of the next section. This procedure will ensure that the assembly will be rigid enough to stand by itself.

This method of assembling very large platforms will impose some additional constraints on the design of the assembler, which must be capable of starting on the side of an existing structure. These constraints will be in the form of appropriately interfacing row ends and special features of the machine, which will depend on the type of column attachment selected. Figure A-7 shows a right end configuration which does permit restart at any row. This technique implies that construction must proceed from the basically triangular configuration of the tetrahedral truss. Figure A-7 also shows that the assembler has the capability of traversing along any edge of the basic triangle and can perform changes of direction to go from one side to the other, or return to the first row position. Alternately, by suitable selection of row ending, the assembler can construct a triangular or hexagonal platform from either side, by going around it as a spider constructs its web.

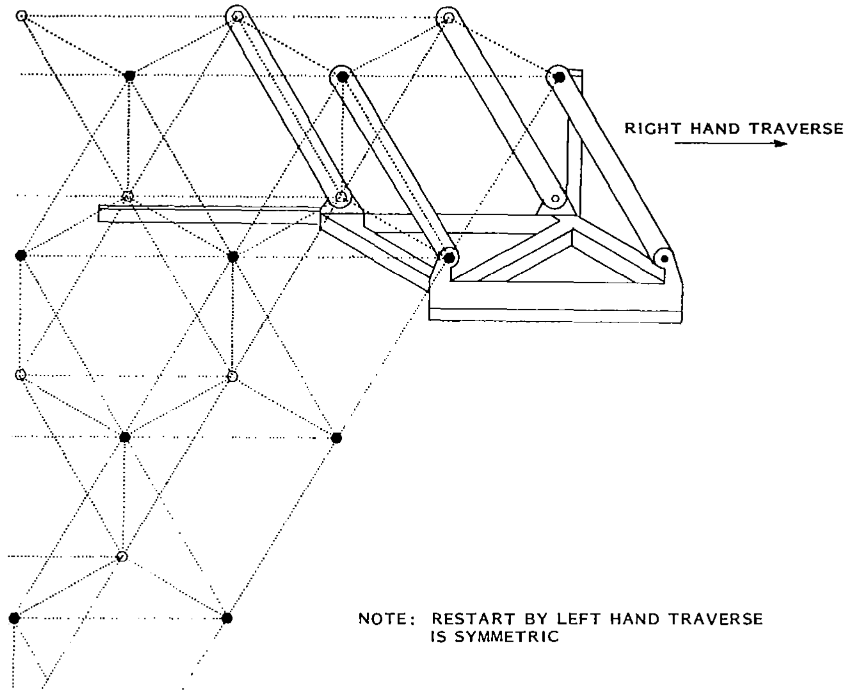


Figure A-7. Right End Configuration Permitting Restart at Any Row.

A1-4 COLUMN INSERTION

In laying out the general configuration of the assembler, care has been taken to ensure direct access to as many column locations as possible (see Fig. A-2), in order to simplify the design of the special manipulators. Only one column has indirect access to its location, as it must be guided past the upper hinges of the machine.

In all cases, it is assumed that stacks of columns will be disposed within the grasp of the manipulators and fed one-by-one as required. For the assembler, as shown on Fig. A-2, this implies stacking at 11 points of the machine, noting that 10 locations are active for any particular traverse (the trailing pivoted arm is inactive during the traverse).

Two methods of supplying columns to the assembler have been considered. The two alternatives are:

a. Each station would receive two canisters containing the half-columns as delivered by the Space Shuttle. A mechanism would connect two half columns to form a complete column, which would be taken over by the insertion mechanism and set in place.

b. In this alternate, half-column connection would be performed by equipment available on the Space Shuttle or at a remote station, and the finished columns, stacked into special holders, would be taken to the assembler and located within reach of the special manipulators. Another variation of this concept is to use hinged half-columns which are deployed and delivered to the mechanism.

The first solution has advantages, as it would permit quick unloading of the Space Shuttle; hence, faster turn-around. However, it requires duplication, up to 11 times, of the column connector mechanism.

The second solution would require that the Space Shuttle stands by while connecting the half-columns or the use of a remote assembly station. It does require one extra step in the fabrication, as the finished columns must be stacked in special holders before delivery to the assembler. On the other hand, the assembler would be somewhat simpler and possibly more reliable, due to the significant reduction in the number of mechanisms.

Conclusion

It has been shown in this section that the proposed space platform assembler can perform all major operations required for the erection of these frames. It has the capability to move along any edge of the basic triangular frame. It can change rows and is capable of restart when building very large platforms.

The problems involved in the insertion of the columns and locking them onto the nodes can be solved with conventional mechanisms.

It is recommended that all operations should be performed under the power of easily replaceable electric motors (dc or steppers) which can be positioned precisely, thereby allowing full control of the assembly by preprogrammed computers. Thus, all routine operations can be automatic, leaving the astronauts with supervisory and emergency duties.

It is envisioned that the assembler should be an independent unit with its own power supply. It should carry solar arrays of sufficient area to cover its own requirements. The possibilities of supplying power via umbilical from an external source such as the 25 kW module has been considered. This is feasible, but would require control of the necessarily loose umbilical cord to prevent it from becoming entangled in the mechanism. It is recognized, however, that the power requirements of this multi-motor device may require solar arrays too large for practical installation on the machine.

A1-5 PARALLELOGRAM FIXTURE, COLUMN INSERTION MECHANISMS

Column Ends - Trajectory Requirements

The general geometry of the automatic rigid parallelogram assembler is shown on Fig. A-8, with indication of the directions of column end insertions for the various members. These directions are shown by arrows, using the usual convention. They are based on the use of the column end connectors in Section 4.1, which imposes a definite direction of entry into the sockets.

Figure A-9 provides a more detailed examination of the trajectories which must be followed by the column ends in order to be inserted into the sockets. Note that the columns having insertion numbers 1, 2, 4, and 5 are the oblique members connecting the upper and lower planes. All these columns must be set in place by moving one end in one direction and the other end in the opposite

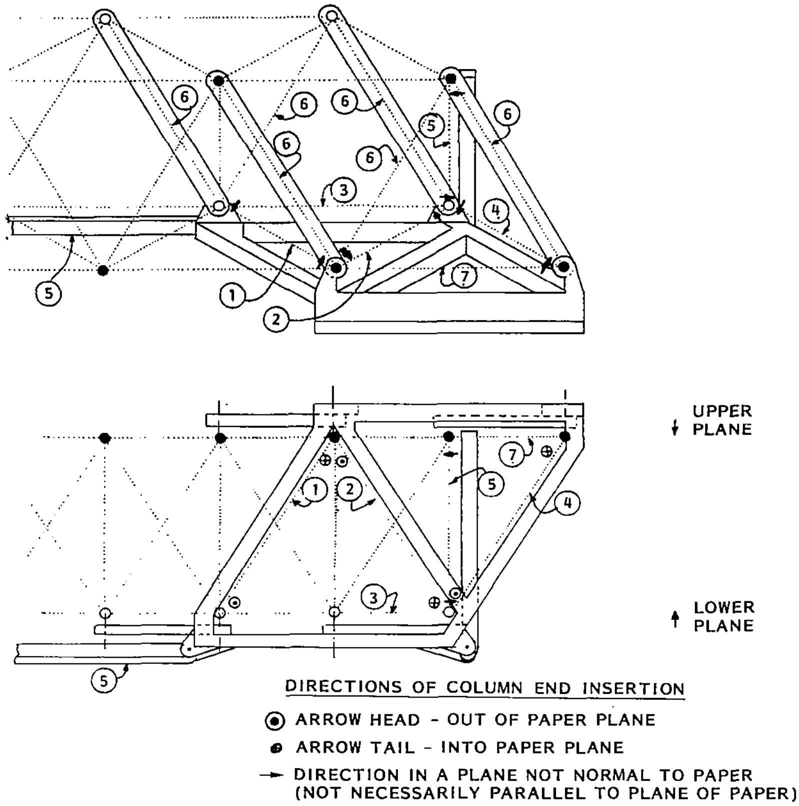


Figure A-8. Rigid Parallelogram Assembler.

direction. This feature is introduced by necessity of making all node joints identical, in order to prevent a cumbersome indexing problem in storage and assembly. Therefore, in a particular projection of one column, the upper node fitting, which is looking downward, has its socket open to the left while the lower node fitting, which is looking upward, is open to the right. This is typical of columns 1, 4, and 5 on Figs. A-8 and A-9. Column 2 is a special case, where the order is reversed by the geometry of the assembly machine, which imposes column loading from the right, instead of from the left, of the structural member.

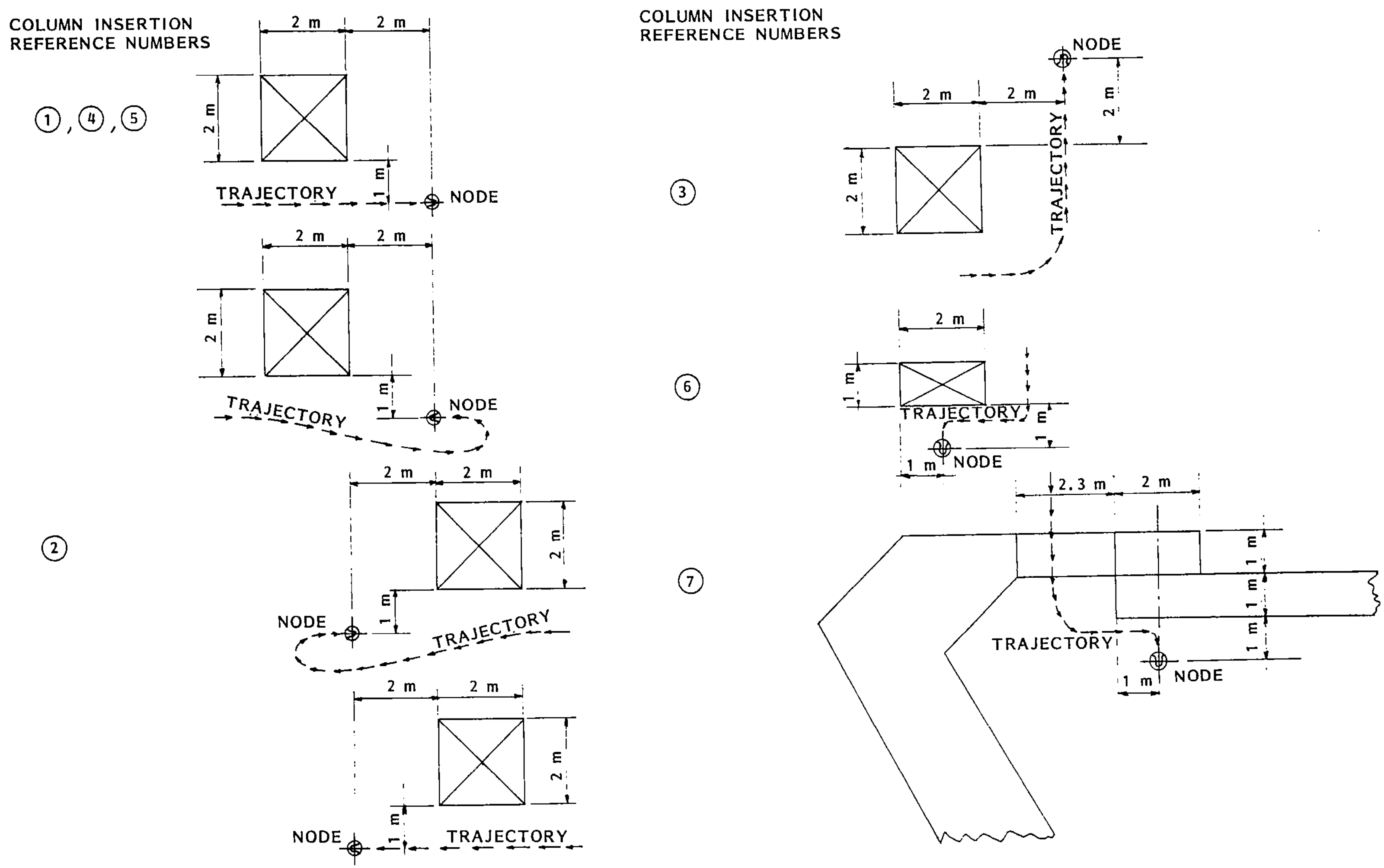


Figure A-9. Column End Trajectories.

Column 3 is to be inserted into sockets facing in the same direction (downward) so that a straight approach trajectory is possible.

Columns 6 and 7 must be inserted into sockets facing in the same direction, toward the assembly machine structural members. In this case, the columns can be manipulated within the one meter gap between the assembler structure and the node joints in such a manner that the final motion is vertical.

A1-6 SPECIALIZED INSERTION MECHANISMS

General Considerations

The design of insertion mechanisms depends to a large extent on the type of node joints to be selected for this application. In this concept, the systems were laid out to satisfy the requirements of the snap-lock node joints in Section 4.1, which require side entry in fixed directions.

The conceptual designs presented here assume that the columns are provided ready to install and loaded in appropriate canisters attached to the platform assembly machine at the required locations. Therefore, column assembly and canister loading must be performed separately from the platform.

Two types of insertion mechanisms are considered in this conceptual study. The first one is based on the use of current Remote Manipulation System (RMS) technology typical of, but less sophisticated than, the main Space Shuttle RMS. In this case, the mechanism, would be used at all column assembly points under computer control. This approach greatly simplifies the logistic problems of maintenance and replacement of defective units. It substitutes software complexity for hardware complexity. The second approach consists in designing simpler mechanisms for each particular location. However, these devices cannot be simplified to the point of being completely independent from computer control. Their main disadvantage is the lack of interchangeability and the associated logistic problems of maintenance and replacement. A trade-off must be made between mechanical and software complexity and logistic problems.

Due to the small size of the node joints, it is most likely that problems of mechanical interference will exist in the assembly of columns radiating from one single joint. It is believed that this can be eliminated by appropriate sequencing of column insertion and, to some extent, by judicious design of the robotic end-effectors.

A1-7 INSERTION MECHANISM BASED ON RMS TECHNOLOGY

In this approach, the basic assembly tool considered is a special RMS having a reach of five to six meters. This instrument would be a scaled-down and simplified version of the current Space Shuttle model and should have enough degrees of freedom to comply with the requirements of the platform assembly machine. Twenty units are required to handle the 10 column positions of the machine.

A description of the RMS motion requirements is presented on Fig. A-10. Note that the motions required to follow the prescribed trajectories are generally fairly simple, especially in the case of insertions No. 1, 2, 4, and 5. Insertion No. 3 has the largest displacement, also requiring wrist rotation. All these can be stowed flat along the platform assembler structure during transit from one work position to the next.

Swing Over Insertion Mechanisms

A type of simple manipulator can be designed for each pair of insertion points, i.e., for each column. Basically, these devices consist of a forearm and the end-effector, mounted with only one degree of freedom at the elbow, as shown on Fig. A-11 for insertion No. 3.

This manipulator has a reach of 2.8 meters and requires two stepper motors for its general operation, plus those needed for the end-effector (another two). In operation, the forearm swings about its pivot and the wrist rotates the end-effector to orient the trajectory along the desired path. The relationship between forearm angle and the wrist angle must be controlled either

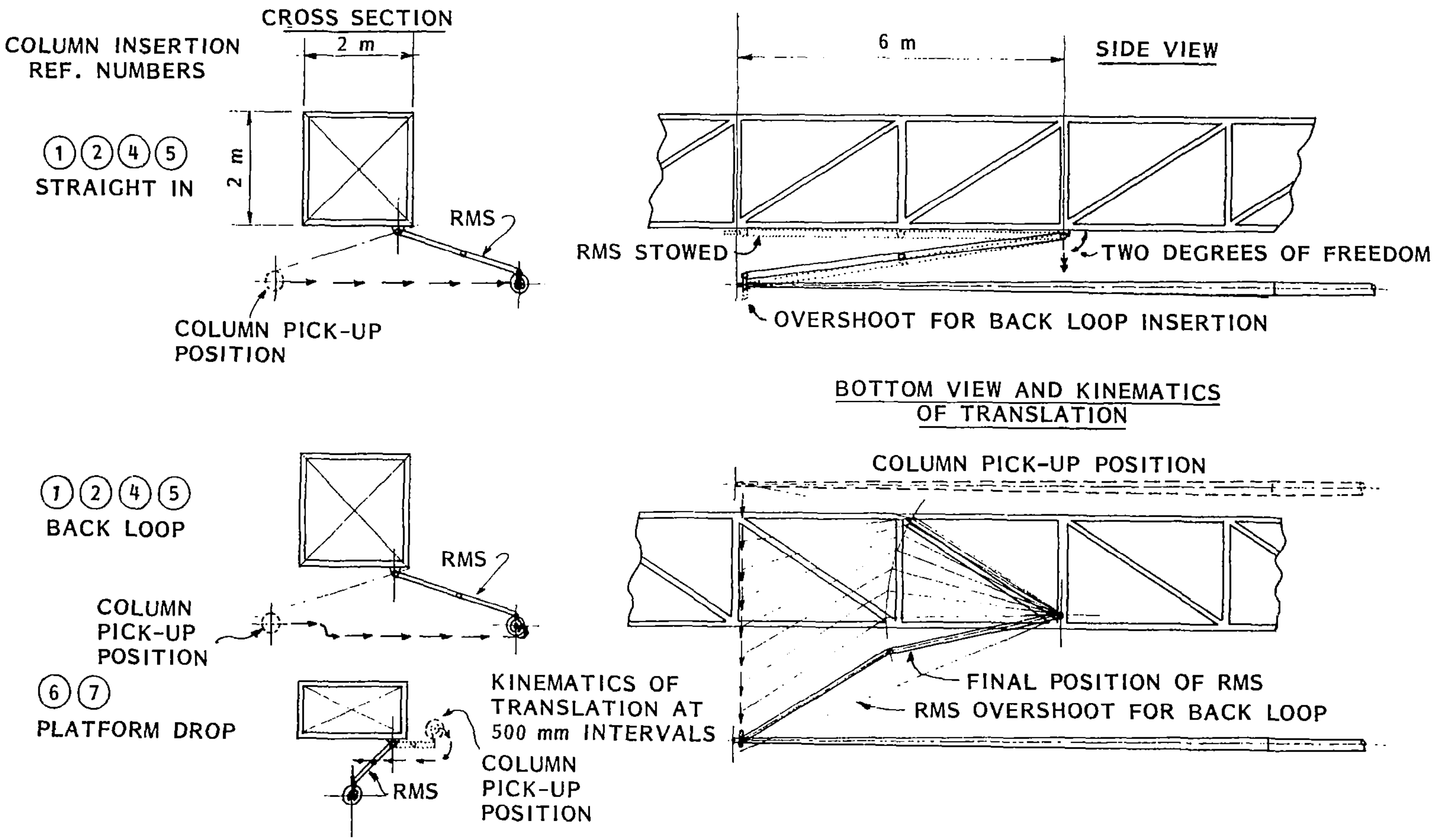


Figure A-10. Column Insertion Mechanism.

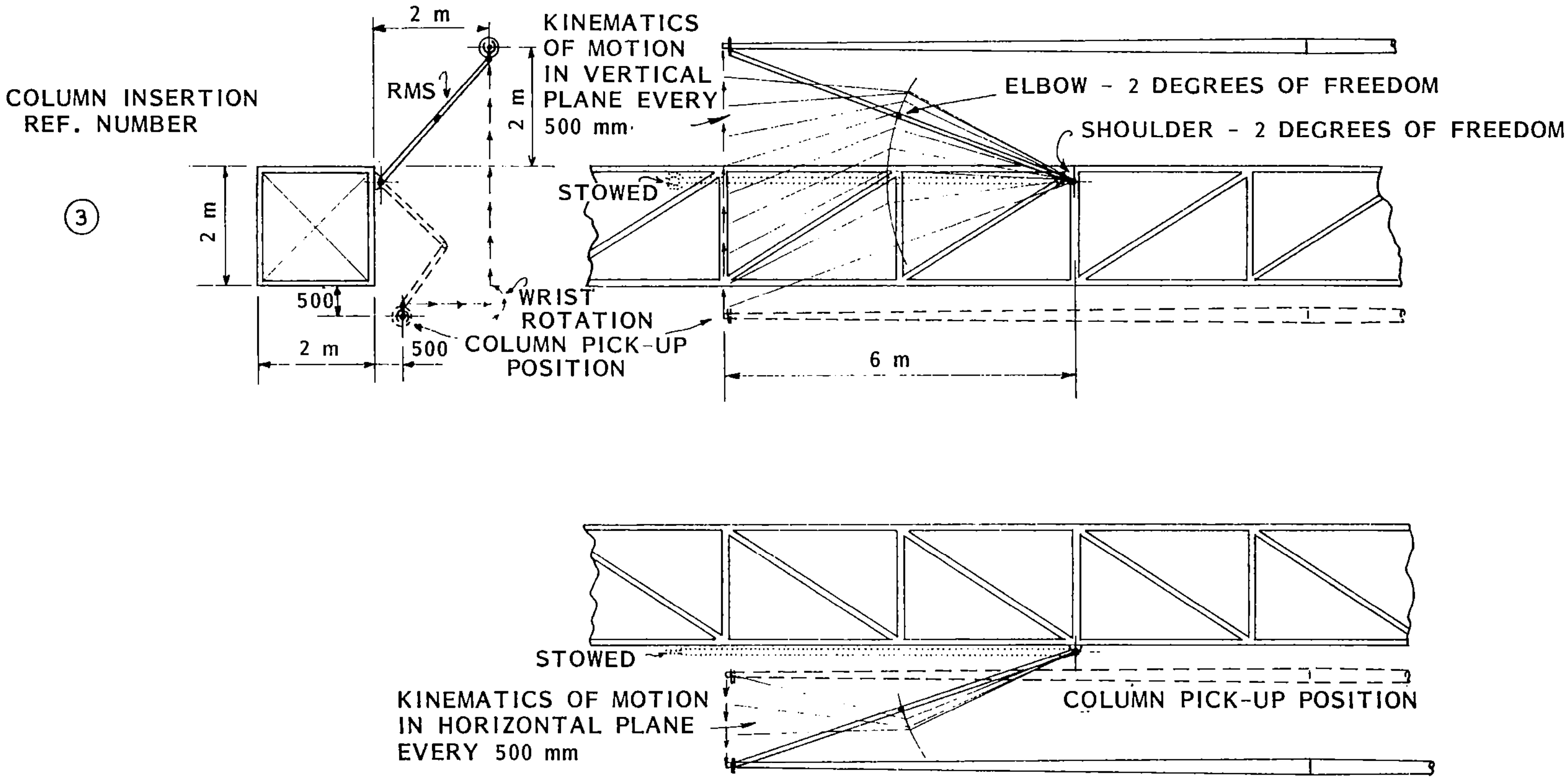


Figure A-10. Column Insertion Mechanism (Concluded).

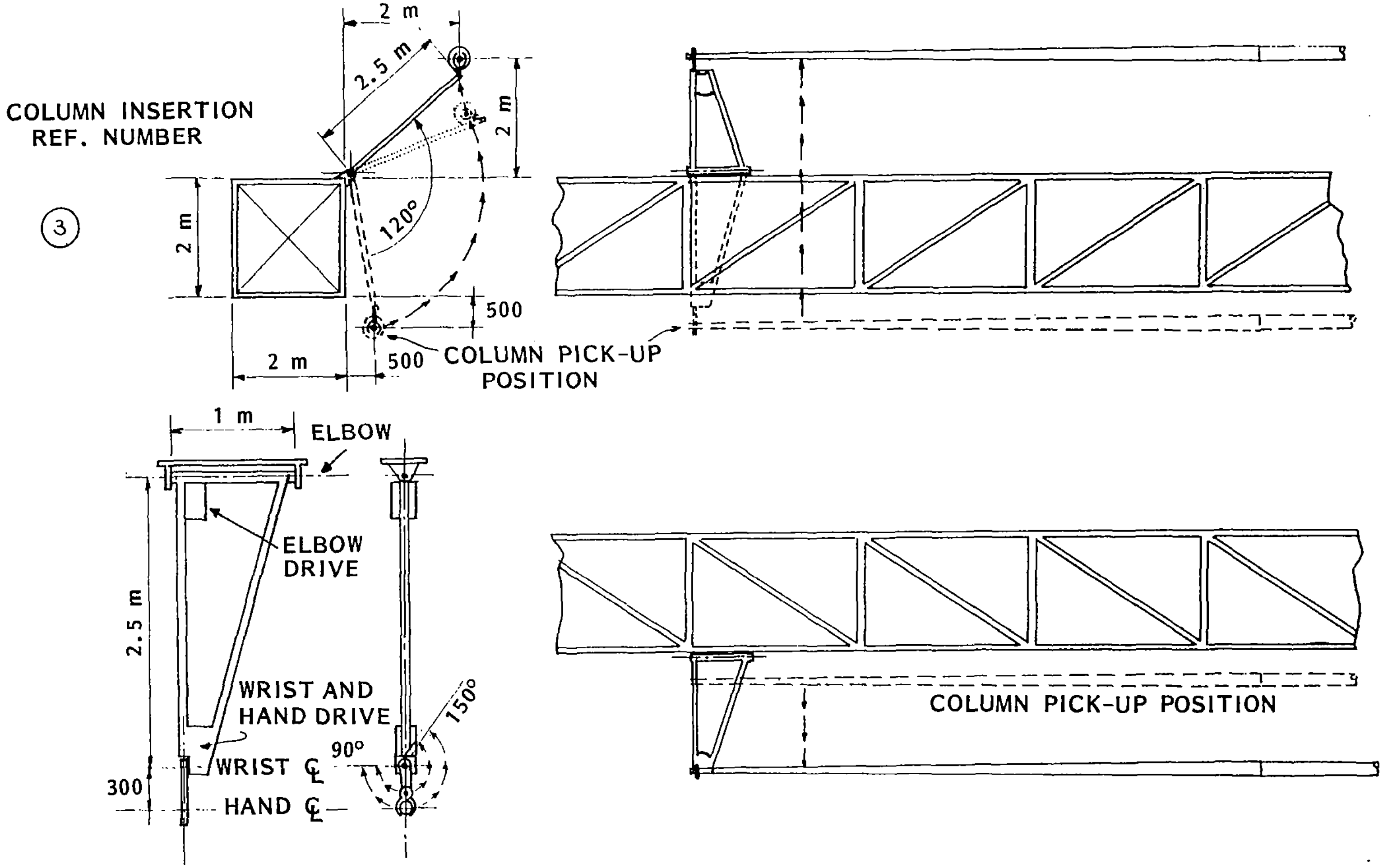


Figure A-11. Swing-Over Type Column Insertion Mechanism.

mechanically, by means of a cam device, or via software from a computer. The final choice depends on the complexity of the required motion.

Application of this concept to insertion No. 6 is shown on Fig. A-12A. In this case, the motion is somewhat complicated by the direction of insertion, which is not close to the tangent of the swing-over arc. It is necessary to overshoot the final position and return with a combined forearm-wrist motion to follow the prescribed path. It seems possible to perform this motion with an electro-mechanical device which will also control the return to the pick-up position with only minimal computer control.

Application of this manipulator at insertion 1, 2, 4, and 5 (oblique columns between upper and lower planes) are shown on Figs. A-12B and A-12C. The kinematics of the manipulator motion is shown on Fig. A-12C for each end of the column. The motion of the wrist, combined with that of the forearm, is set up to provide a rectilinear translation of the column end, either to the right or to the left, according to the direction of entry into the socket. Note that the end-effector trajectory is constrained by the geometry of the manipulator so that a possibility of interference exists with the columns already inserted. In general, this problem can be averted by assigning a sequence to the column insertion so that an unobstructed path is available in all cases. An investigation should be performed at a more advanced stage of the design.

The application of this mechanism to column insertion No. 7 is shown on Figs. A-12D and A-12E. The geometry of the platform assembly machine in this area imposes more severe constraints on the design than at any other location; the attachment of the forearm hinge must be offset with respect to the column end. Two options are available; attaching the hinge fitting to either the right, or to the left, leg of the structural member (as shown on Fig. A-12C). The left leg solution was selected as typical and it was found necessary to provide an additional truss to locate the hinge in the desired position. Details of the swinging forearm are shown on Fig. A-12E, together with the kinematics of insertion. The motion starts by a 140 degree wrist rotation,

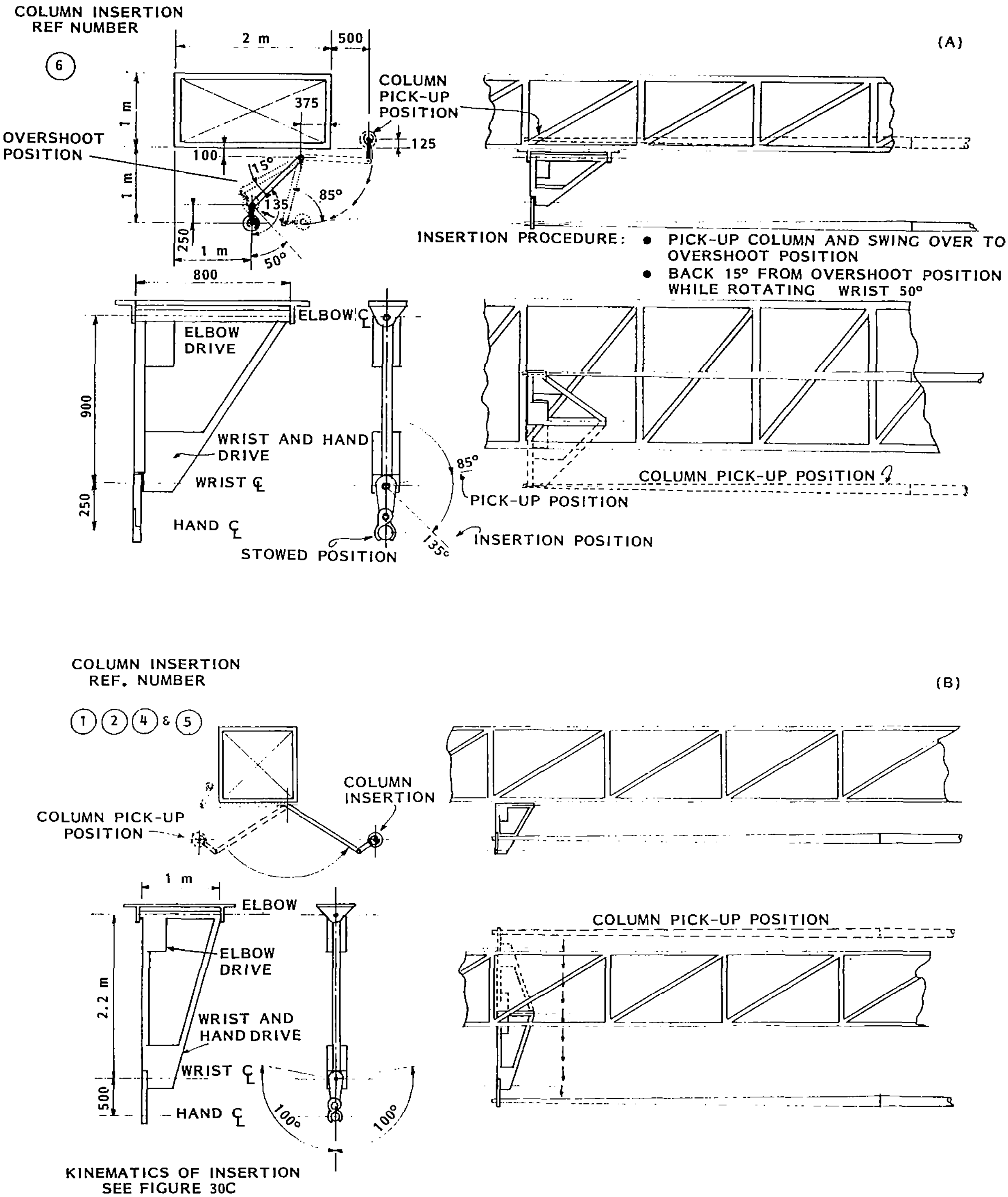
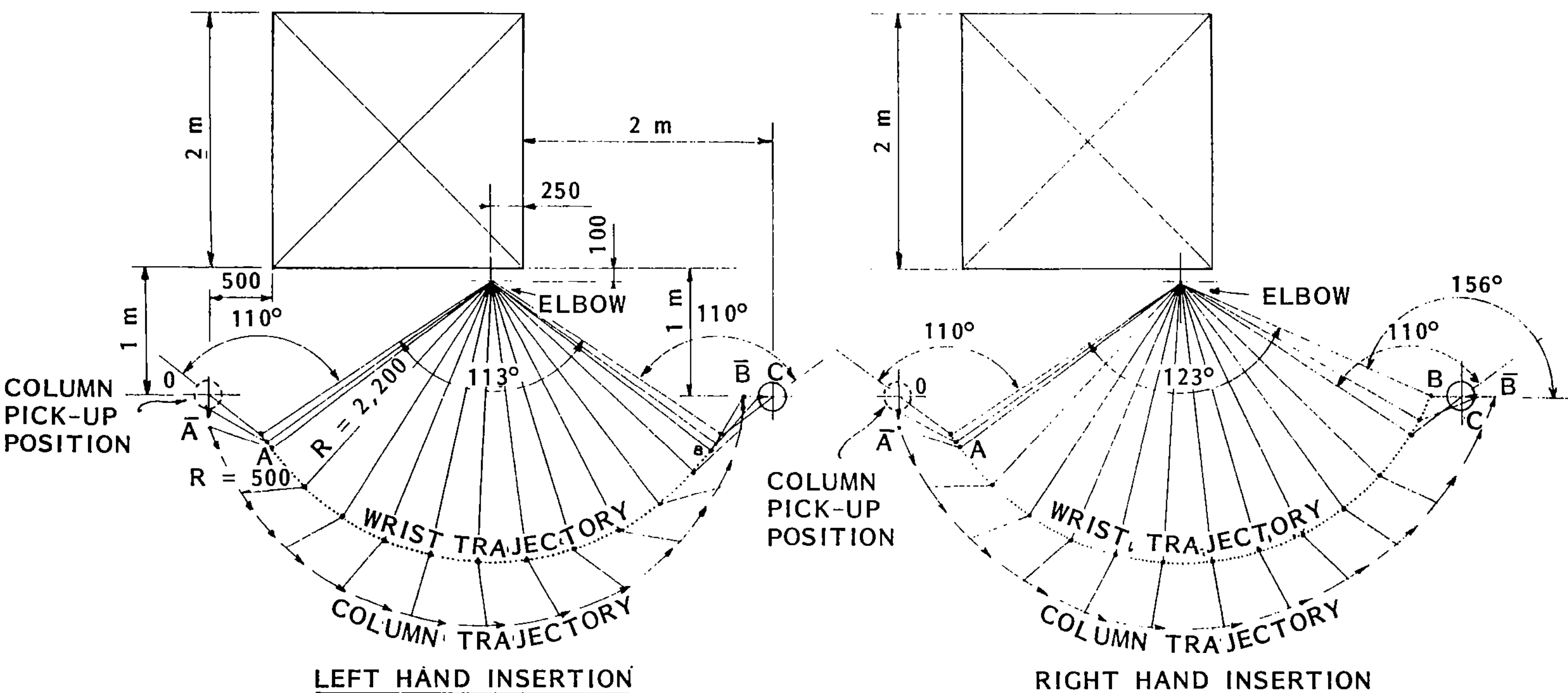


Figure A-12. Application of Swing-Over Concept.

KINEMATICS OF INSERTION - COLUMNS (1) (2) (4) & (5) (C)



- FROM A TO B, ELBOW/WRIST ROTATIONS = $\frac{1}{1.4}$
- FROM A TO B, ELBOW/WRIST ROTATION = $\frac{1}{.95}$
- RECTILINEAR COLUMN TRAJECTORIES FROM O→Ā AND FROM B̄ TO C FOR BOTH LEFT AND RIGHT HAND INSERTIONS

Figure A-12. Application of Swing-Over Concept (Continued).

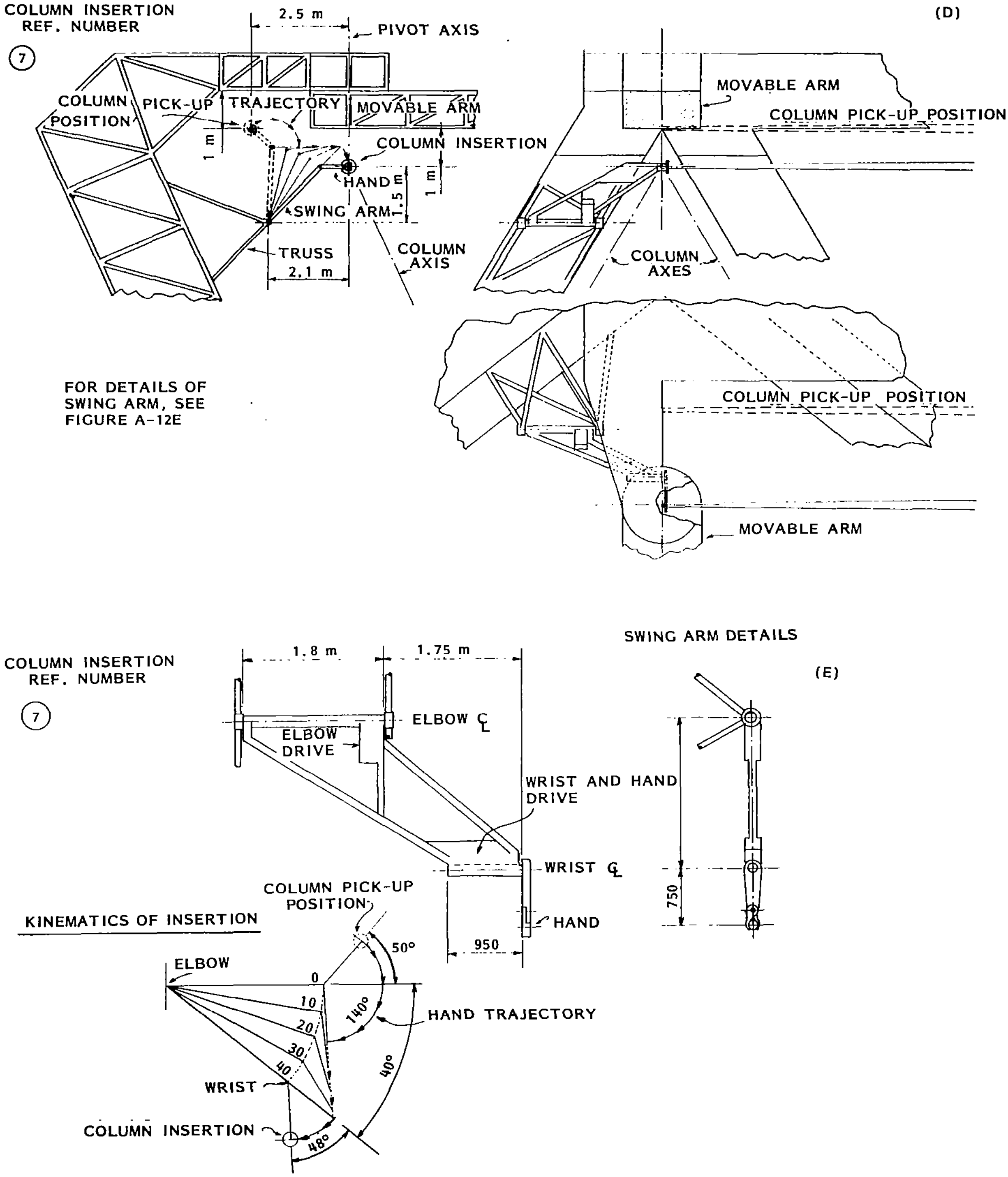


Figure A-12. Application of Swing-Over Concept (Concluded).

followed by a combined rotation of the wrist and forearm, which brings the manipulator fully extended against a stop. The final insertion motion is provided by a 48 degree wrist rotation. Performed in reverse, this motion brings the manipulator back to the pick-up point.

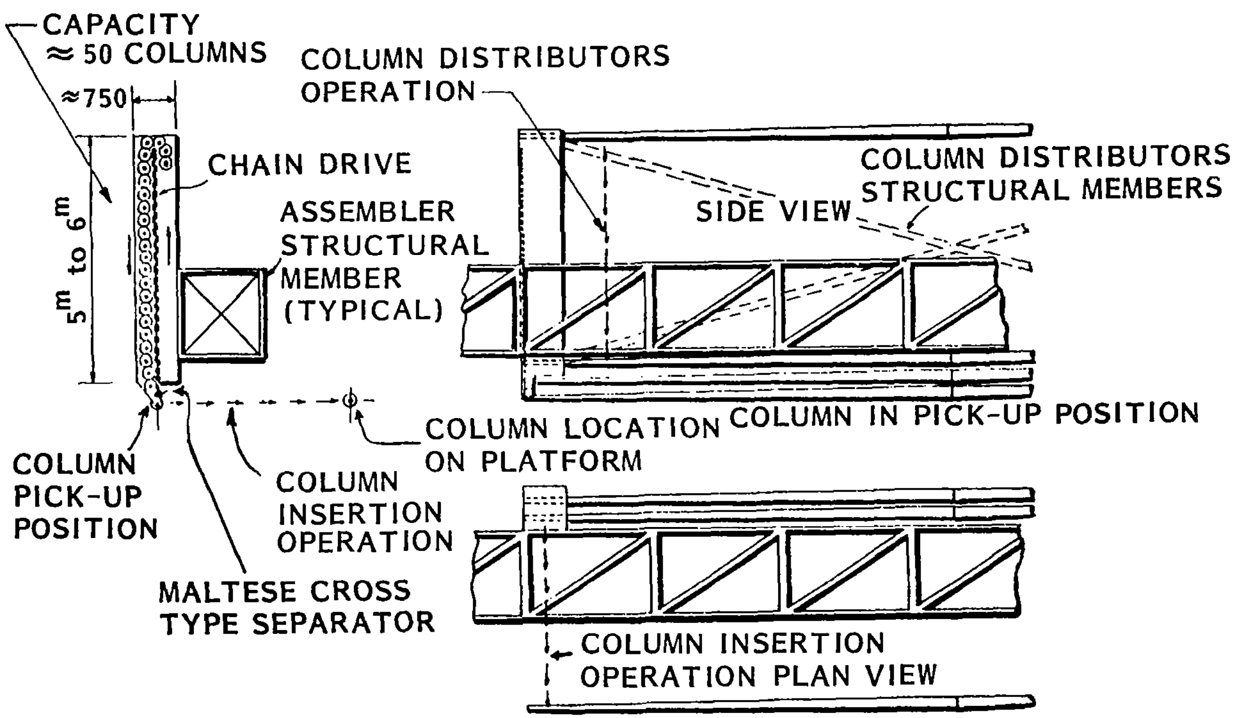
This study shows that insertion mechanism can be designed to cope with the requirements of all column insertion positions on this platform assembler. At least four different mechanisms are required, of which two types appear to be simple enough to provide the required trajectories by means of a cam and linkage system. A purely mechanical system does not appear practical, due to the necessary mechanical complexity and its associated degraded reliability. Consideration should therefore be given to the application of electro-mechanical devices under control of a computer.

A1-8 COLUMN SUPPLY CANISTERS

Provision must be made for the installation of column supply canisters at 11 locations on the platform assembly machine. However, during a left hand or a right hand traverse, only nine locations are active. Therefore nine canisters must be loaded on the machine for normal operation.

The canister design shown on Fig. A-13 is based on the assumption that the half-columns will be assembled together by a separate machine operating at some distance from the platform under construction. This machine would obtain half-column canisters from the Space Shuttle, extract the components in pairs, and maneuver to connect them as required. The completed columns would then be fed into the loading canisters.

The loading canisters would hold at least 50 complete columns. The distribution mechanism is seen as an endless chain drive, equipped with spring-loaded clamps designed to hold the columns by each end, leaving clear access to the manipulator claw holding surface. At the exit of this canister, a device based on the Maltese cross principle would disengage the columns from the chain drive and advance them one-by-one to the pick-up position.



NOTE: THE USE OF THIS COLUMN DISTRIBUTOR (OR A SIMILAR MODEL) IS REQUIRED WHEREVER THERE IS INSUFFICIENT CLEARANCE FOR ON-SITE COLUMN ASSEMBLY

Figure A-13. Typical Column Distribution System.

These canisters would consist of two symmetrical units, each containing a complete chain drive. These two units, linked by a framework, form the canister. The general dimensions of one of the canisters is approximately as follows: length 20 meters, width 0.80 meters, height 0.5 meters, plus one meter for each eight columns. Therefore, a 50 column unit would have a height in the order of seven meters.

The structure of these canisters must be designed to provide sufficient rigidity, especially in torsion, so that the columns do not risk being damaged during canister transit and loading onto the platform assembler.

A1-9 NODE RETAINERS AND SUPPLY CANISTERS

With a few modifications, the node retainers are similar to the model to be described in Section A2-4. (Figs. A-25 and A-26). The node canisters make use of the same principle to load the retainers.

In this case, the node retainers are mounted at fixed points of the platform assembler arms, as shown on Fig. A-14. A 90 degree swinging capability is provided for picking up the node fittings from the canisters and stowing the retainer arm during traverse transits. A schematic of the retainer arm drive unit is given in Section A2-4.

As shown on Fig. A-14, the node supply canisters can be made to dispense the nodes either to the right or to the left. Loadings to the left appear to be a better compromise, as it may be more easily adapted to all node pick-up points. The internal mechanism of these canisters will consist of chain drives and special locking devices designed to secure the nodes during launch. The capacity of these canisters is dependent on the size of the node fittings. For example in the case of the nodes of Section 4.1, the volume required is, per node, a 180 mm cube. Thus, a canister having approximate dimensions: 1.10 meters x 1.10 meters x 0.25 meters would contain 36 nodes. Such a canister could be fitted easily within the platform assembler framework, as shown on Fig. A-14. If a larger number of nodes per canister is

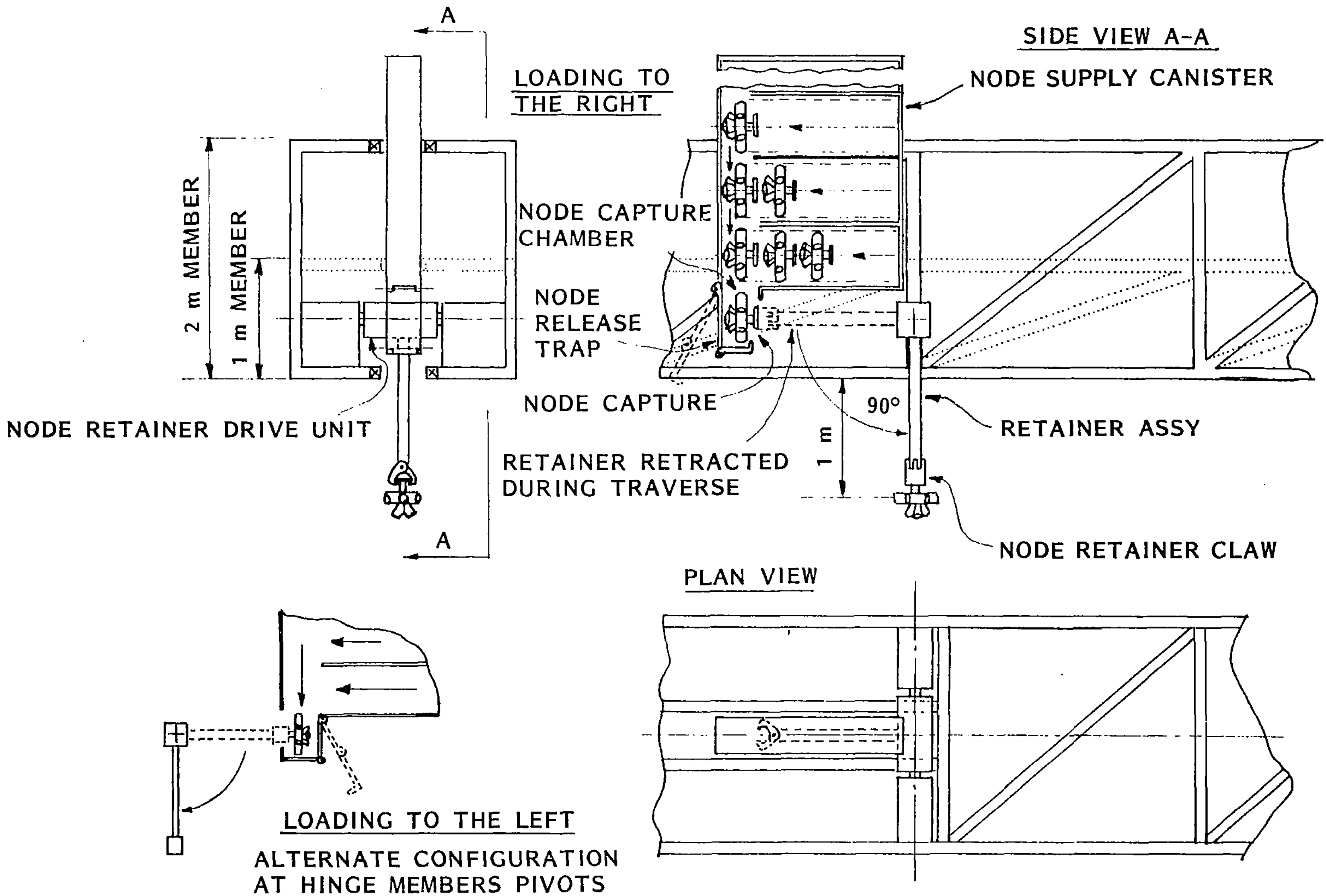


Figure A-14. Node Retainers and Supply Canisters.

desired, a size 2.20 meters x 1.10 meters x 0.25 meters would contain 72 nodes and still remain reasonably small.

The retainer node capture procedure is similar, in principle, to that described in Section A2-4. The node holder is positioned with respect to the node retainer at such a distance that, when the retainer is rotated 90 degrees, the holder will fall inside the claw. Then, the following sequence is activated:

a. The claw is closed to secure the node joint.
b. The canister node joint holder is released.
c. The release trap is opened.
d. The node retainer is rotated to its down position.
e. The release trap is closed.
f. The canister node joints are advanced by one step to complete the cycle.

A1-10 PLATFORM SPEED OF ASSEMBLY

The following estimate of construction time is based on one Shuttle load of 2700 columns and rotation time of 14 days.

It is assumed that half-column assembly into full columns is carried out independently from the platform construction and at a speed matching the machine requirements.

Platform Assembler Reloading

The platform assembler reloading frequency depends on the size of the canisters, especially the column canisters. Considering a typical 50 column canister, and 2700 columns per Shuttle load, 54 canisters will be loaded. Since nine canisters must be loaded on the machine for normal operation, unloading empty canisters and reloading with full canisters will be performed at least six times for each Shuttle load. Although some mechanical devices can be

designed to assist in performing this operation, full automatic loading does not appear to be practical, due to the large size of the column canisters and the relatively large distance which must be traveled from the half-column assembly machine to the platform assembler. Therefore, it seems advisable to consider EVA as the main loading method. The total loading will consist of nine column canisters and four node canisters. Assuming a team of seven astronauts, four maneuvering the canisters and two giving directions, one loading operation should require somewhere between four to eight hours. Therefore, for the six loadings required, the platform assembler will remain idle for 24 to 48 hours.

Time to reload the assembler using remote column assembly constitutes the largest single item in establishing the erection time line for this assembly system. It may be possible to significantly decrease the loading time by using larger canisters. A tradeoff study is required to obtain the most efficient loading system. This study should include the dynamic loading and platform strength and rigidity parameters.

The reloading time is reduced considerably by using the concept described in Section 5.

Column Insertion Mechanism Operation

The insertion mechanism designs considered for this application are intended for transferring the columns over short distances not exceeding four to five meters. The average distance is about four meters and a moderate traveling speed of 0.25 m/sec may be assumed. The transit time from column pick-up to insertion is 16 seconds. The mechanism return stroke may be performed at double speed (eight seconds) and the total installation time for one column can be established as follows:

Column pick-up:	10 seconds
Column transit:	16 seconds
Column lock-up:	15 seconds
Mechanism return to pick-up:	8 seconds
Total	49 seconds

Since it has been noted that the trajectories of column ends can intersect, the possibility of mechanical interferences exist. Therefore, it is necessary to determine a sequence of column insertion which will prevent collisions. An examination of the machine operation leads to the conclusion that, on the average, two columns can be inserted simultaneously. The total insertion time for 2700 columns is approximately:

$$t = \frac{2700}{2} \times 49 = 66{,}150 \text{ sec } (18.4 \text{ hr})$$

Assembler Operation - Traverses

It is assumed that the arms of the platform assembly machine can be swung at an average angular velocity of one degree per second. A 60 degree displacement will be covered in one minute, corresponding to a 20 meter lateral translation of either the main frame of the machine or of any arm.

The time required to perform one step of a traverse, excluding column insertion, is computed from the motion described in Section A1-3, Fig. A-3.

Under the above assumption, the translation shown on Fig. A-3A, A-3B & A-3C could be performed in one minute, but some time must be allowed for the release of four nodes and the capture of two nodes. Therefore, a total time of two minutes is considered for this motion.

On Fig. A-3D two arms are swung over, one after the other. This motion would require two minutes. It is assumed that new node fittings can be secured at joints N1 and N2 during this operation, so that no additional time is required for this function.

On Fig. A-3E, two other arms are disconnected, swung over, and reconnected to node fittings, again one after the other so that the time required is two minutes.

The total time for one traverse translation cycle is therefore:

Main frame translation:	2 minutes
Rotation of two arms:	2 minutes
Rotation of two arms:	2 minutes
Total	6 minutes

After each translation, the platform assembly machine inserts nine columns. The Space Shuttle load of 2700 columns requires 300 traverse cycles. These traverse cycles will include a number of row changes, depending on the size and shape of the platform being constructed. The time requirements for this operation (described in this Appendix) is 10 to 15 minutes; or, twice the time of a normal traverse cycle, 12 minutes. Assuming that the platform consists of 10 rows of 30 traverse cycles (i.e., 600 meters x 173 meters), this is equivalent to adding 10 traverse cycles (i.e., a total effective number of traverses = 310 and the corresponding traversing time: 310 x 6 = 1860 minutes = 31 hours). For the above estimate, the row change is considered as a standard traverse cycle plus six minutes, since a set of columns is inserted during this operation.

Total Time Required for the Assembly of One Space Shuttle Load

Under the set of assumptions formulated in the preceding paragraphs, a full Space Shuttle load consisting of 2700 complete columns and 600 node fittings would have an erection time as follows:

Traversing time:	31 hours
Column insertion:	18.4 hours
Machine reloading:	24 to 48 hours
Total	73.4 to 97.4 hours
Total 8 hour days	9.2 to 12.2

Remarks

This motion time study is based on engineering estimates which reflect experience with reasonably rigid and fairly well damped systems. This may not be the case for the structure under consideration here, due to its large size. It must be kept in mind that traverse operations may require additional time to allow sufficient decay of oscillatory motions. The traverse times quoted above were considered as reasonable and can probably be achieved with an adequately rigid structure and an appropriate procedure to minimize the effects of start and stop transients.

Similarly, the unloading/reloading time is based on an incomplete knowledge of the conditions in which the astronauts must work during EVA. It is conceivable that a number of aids can be devised to assist them and ensure correct positioning of the canisters, thereby speeding up the process. It is also obvious that the number of astronauts available to perform this task may have a significant effect in reducing the time required. The estimate presented here is based on a four-man crew working one eight-hour shift. However, if column assembly takes place on the assembler beams only one loading is required to exhaust the supply of columns from the Orbiter, and only EVA monitoring will be required after loading.

A1-11 PLATFORM ASSEMBLER STRUCTURAL DESIGN

The structural design philosophy of this platform assembler follows the model to be described in Section A2-4, to remain compatible with storage in the Space Shuttle cargo bay in knocked down and stowed form. The structural members would consist of a set of deployable segments which can be assembled

together in orbit without special tooling requirements. As shown in Section A2-4, these structural members, upon activation of a simple release, are automatically deployed under the power of spring actuators and locked in the open position without external assistance. However, for safety purposes, and to increase rigidity, additional latches must be locked manually after deployment.

The dimensions of the structural members were selected to meet, in the stowed conditions, the constraints imposed by the size of the Space Shuttle cargo bay. The maximum cross-section is therefore two meters x two meters (four meters x approx. 0.2 meters stowed). The movable members were laid out with a one meter x two meter cross-section, counting on the additional stiffness introduced by the column canisters to provide sufficent rigidity in lateral and vertical bending, without undue increase of the movable masses.

A1-12 TECHNICAL DISCUSSION

This conceptual study of the rigid parallelogram assembler shows that relatively simple mechanisms can be devised to insert columns with various types of end connectors.

The two types of manipulator concepts investigated here can be equally successful in inserting columns. The standard RMS adaptation is already a well developed device which can be scaled down to the appropriate size and designed to meet the particular requirements of this application. Its main advantage is its universality, which greatly simplifies the interchangeability and the associated resupply problems.

The forearm type manipulators are attractive because of their inherent simplicity but they must be uniquely designed to fit each different application. The complete installation would require four to five designs, based on the same general principle.

The operational time analysis shows that the time required to assemble a full 2700 column Space Shuttle load is 9 to 13 days, on a one eight-hour shift per day basis. Note that about half of this time is devoted to loading and unloading column and node joint canisters to the platform assembler. This operation must be performed six times for each full Space Shuttle load. Column canisters must be replaced at nine points on the platform assembler and node canisters at eight points. This operation, which must be performed by means of EVA, is necessarily time consuming. Increasing the size of the canisters will reduce the frequency of the loading-unloading operation. However, there are limits to canister size from the standpoint of handling in orbit and from the constraints imposed by the platform assembler configuration and operation.

Column insertion time is a problem dependent on a careful analysis of insertion timing. By design requirements, the node joints are relatively small. The insertion device must work in crowded quarters as it inserts columns. In order to prevent interferences, it is necessary to assign each operation in a particular sequence. Careful consideration of this issue may result in significant saving in operational time.

In view of the size of the platform assembler and its large moving components, rigidity requirements based on jigging practice at ground levels became inapplicable. It will be necessary to accept a significant amount of flexibility in this structure, as the appropriate stiffness will require an unacceptable weight increase. Damping will be largely limited to inherent structural damping unless discrete dampers are installed on the platform during construction. The dynamic response problems associated with traverse motions of this machine may affect the operational time. This would most likely be the case without damping, and time should be allowed to let residual transient motions decay to safe levels before continuing operation. This issue cannot be considered in detail in a conceptual analysis as presented here. It requires a definition of the structural members.

A1-13 CONCLUSION

In general, solution of the problems associated with insertion of columns and node joints on this platform assembler appears feasible. Solutions presented provide two alternative methods of performing these tasks. Other devices may be profitably adapted.

The structural members, provided they remain a reasonable size, can be manufactured on the ground and stowed aboard the Space Shuttle in a collapsed configuration, to be deployed and assembled in orbit.

A2-1 TRACKED ASSEMBLER

This assembler has the capability to perform essentially the same operations as the rigid parallelogram assembler. However, it does not require the multiplicity of similar mechanisms, which is prevalent in the earlier concept.

This feasibility study considers the basic operation of the assembler and ensures that the design provides adequate access to each column location. In particular, this design leads to a fairly rigid structure, which provides precise positioning of the nodes. It is based on the following assumptions:

- Independent operation from the Space Shuttle, except for receiving supplies of nodes and columns, and life support equipment

- Powered via solar array for self sufficiency

- All routine assembly operations under computer control

- Supervised by astronauts provided with living quarters

- Capability to perform non-routine operations, either under manual or programmed control

- Assembly of the machine in orbit via EVA, without special tooling requirements; partly deployable structure.

Note that this assembler has the capability to traverse along any side of the basic equilateral triangle and its fabrication capability can be adapted to any circumstances by changes in software. Very large platforms can be fabricated in convenient stages whenever the first row is a slender beam which could become unstable. In such a case, the machine would start the construction of a triangular element of safe dimensions which can be extended by working around it to build up the desired shape. In performing these operations, the machine remains connected at all times to the edge of the platform, avoiding complex and risky separation and relocation (docking).

Although the present study considers the case of the 20 meter columns, this assembler can be adapted to other sizes, provided provisions are made for appropriate adjustments. However, the length of the track chains imposes a restriction, since it must always be the sum of a number of node-to-node lengths. It also appears that for node-to-node lengths less than five meters, there is a risk of crowding the operation of the robotic column insertion arms.

A2-2 GENERAL PRINCIPLE

Assembler designs concentrating their attention on the major task of handling the columns and setting them in place are incomplete, as secondary tasks must also be performed (for example, locking the column/node joints under specified preloads). In order to provide the necessary versatility, some specialized devices, such as heavy duty insertion mechanisms, would have to be added. This insertion mechanism is a very simplified version of the Orbiter RMS system.

Noting, however, that the insertion mechanism can provide a means of performing both primary and secondary tasks, an assembler can be designed to take advantage of this capability. Furthermore, by coupling the insertion system with endless tracks carrying the node retainers, a configuration such as that

shown on Fig. A-15 evolves into a complete machine capable of performing all required operations. The basic principles of the design of this assembler are as follows:

- Specialized heavy duty insertion mechanisms to perform all required column manipulations within a rigid framework, which ensures precise positioning of node fittings.

- Node fitting lockup also performed by a special device mounted on the insertion device.

- Node retainers mounted on endless tracks at the correct node distance intervals, and having the capability to capture or release node fittings and rotate them to the required orientation.

- Traverse motions obtained by activating the endless tracks and operating the retainer end effectors to capture or release node fittings following a computer controlled hand-over-hand procedure.

- Row change obtained by disconnecting and retracting all node retainers and repositioning the platform under construction by means of the four insertion mechanisms to reconnect the retainers in the appropriate position.

- Automatic capture of new node fittings from canisters placed at the ends of each track.

- Automatic supply of fully assembled columns provided at two points on the main frame of the machine.

- Compact stowage of the machine in the Space Shuttle cargo bay and simple on-orbit assembly without need of special tooling.

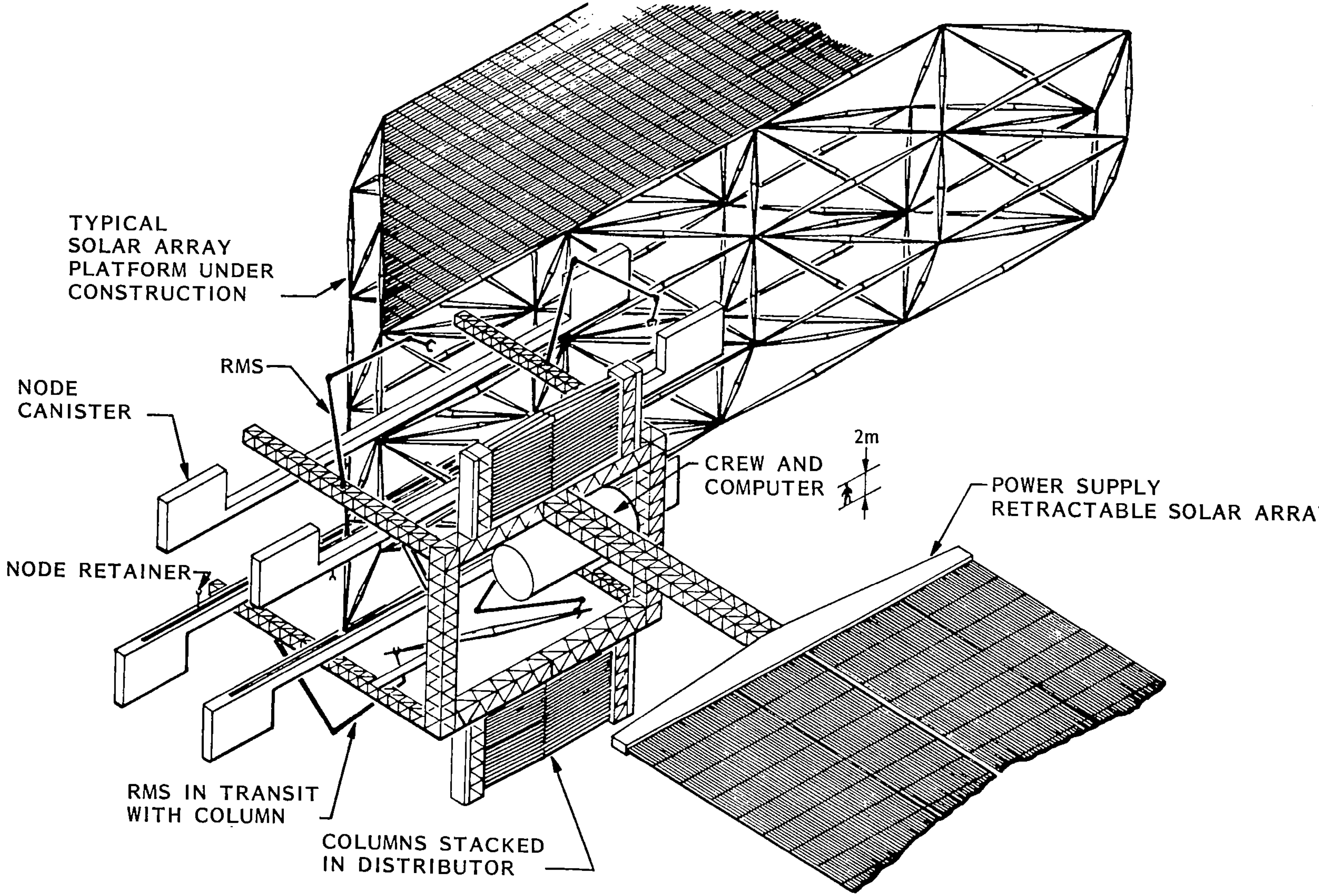


Figure A-15. Automatic Assembler, Track Type.

- Easy on-orbit removal and replacement of machine components for refurbishing or repairs.

A2-3 ASSEMBLER CONFIGURATION

General Configuration

The general configuration of this assembler is shown on Fig. A-15 and A-16. It consists of four tracks, two upper and two lower, which are supported by a rigid framework. Each component is a Warren type framework, designed to provide good bending and torsional stiffness. The four insertion mechanisms are mounted on the cantilever beams of the main frame. All operations are to be carried out within the quadrangles defined by the tracks and beams. Column storage and node canisters are shown in the figures.

Position of the assembler with respect to the platform under construction is shown on Fig. A-17, looking in the axis of the tracks. A distance of one meter between the platform and the tracks has been selected as a compromise between the stiffness requirements of the node retainer system and a reasonable clearance necessary for the row change operation of the machine.

The general dimensions of the main frame are shown on Fig. A-18, for reference. These dimensions are intended to provide a starting point for the design. The structure is subdivided into a number of elements, not exceeding 16 meters in length, to comply with the Space Shuttle cargo bay length. These elements are connected together by structural joints (SJs) designed for quick and automatic locking, using toggle type latches, which can be operated without specialized tools during EVA activity.

A definition of the major structural elements is shown on Fig. A-19. The total assembly consists of 28 structural elements, plus a number of mechanisms, such as end of track drive, to which must be added crew/computer compartment, power supply, etc.

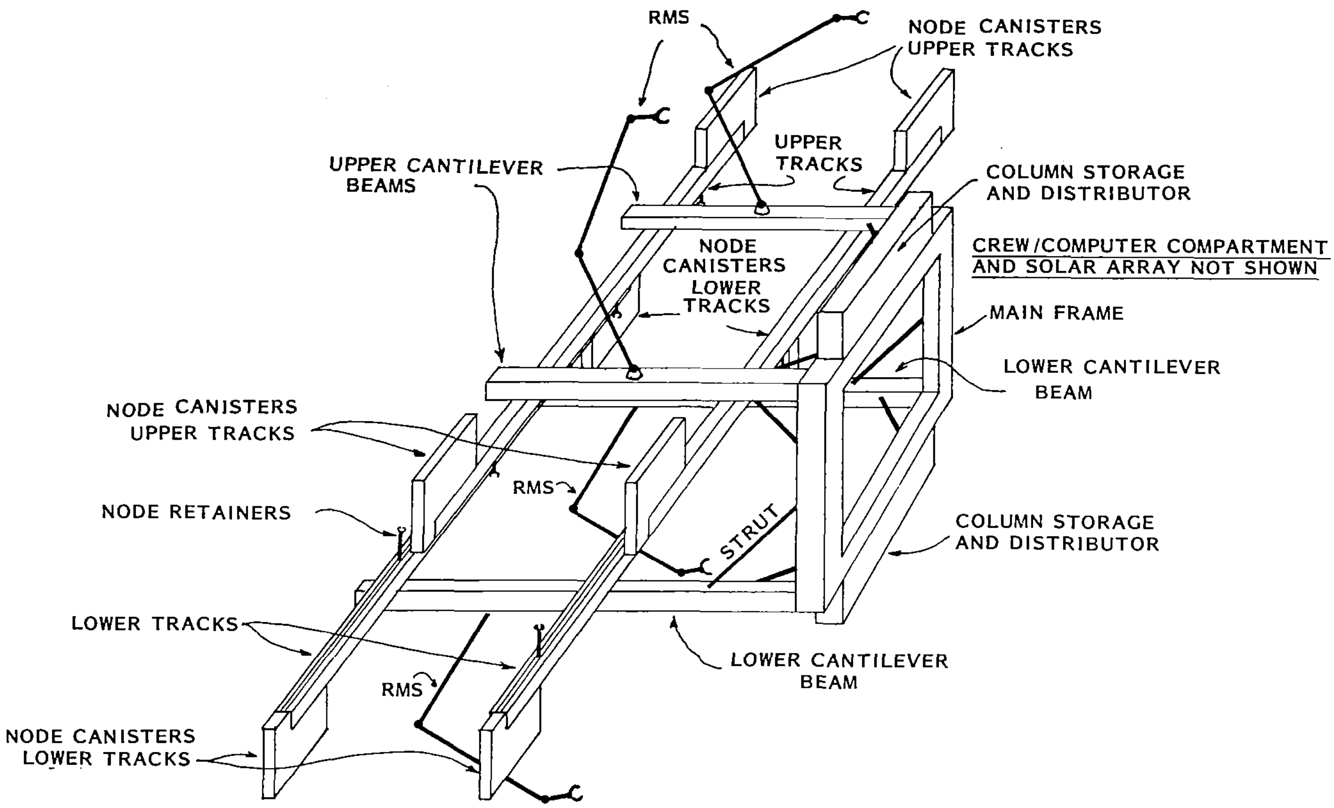


Figure A-16. Tracked Assembler General Concept.

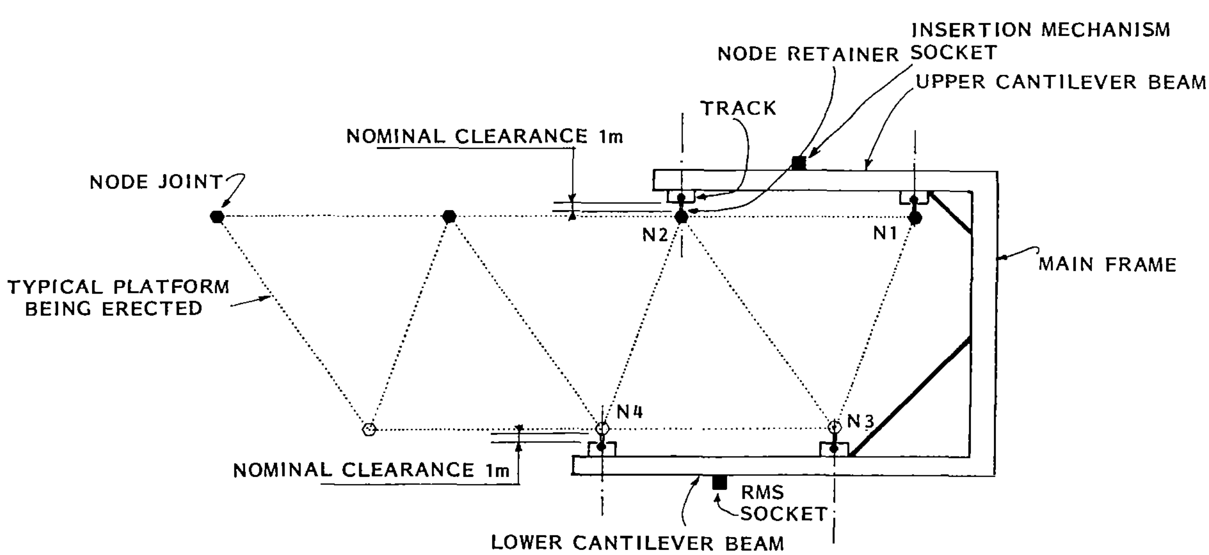


Figure A-17. Tracked Assembler Side View.

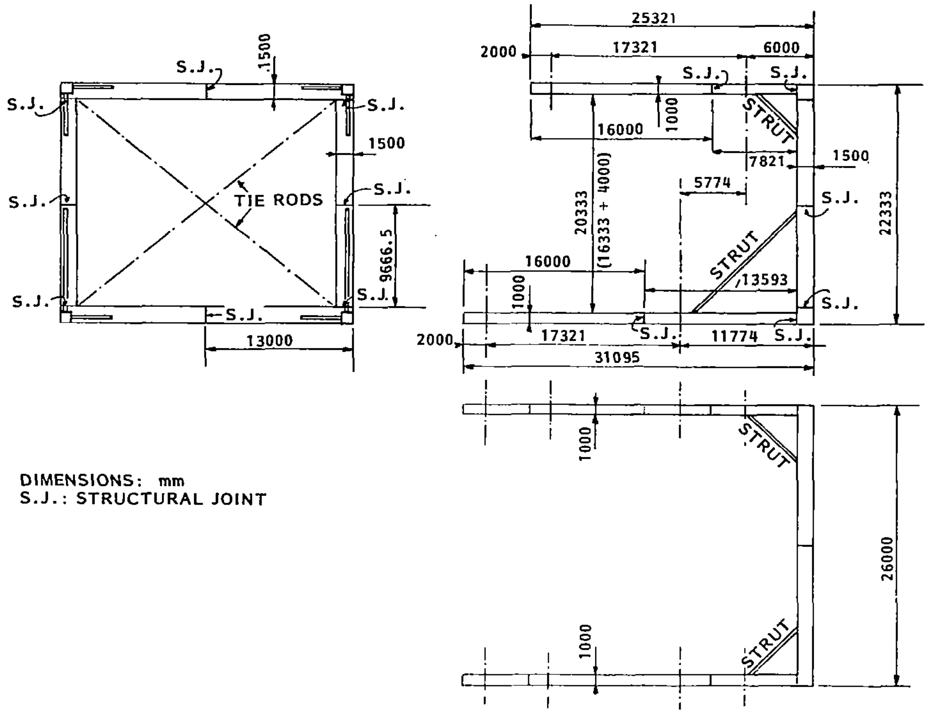


Figure A-18. General Dimensions of Main Frame.

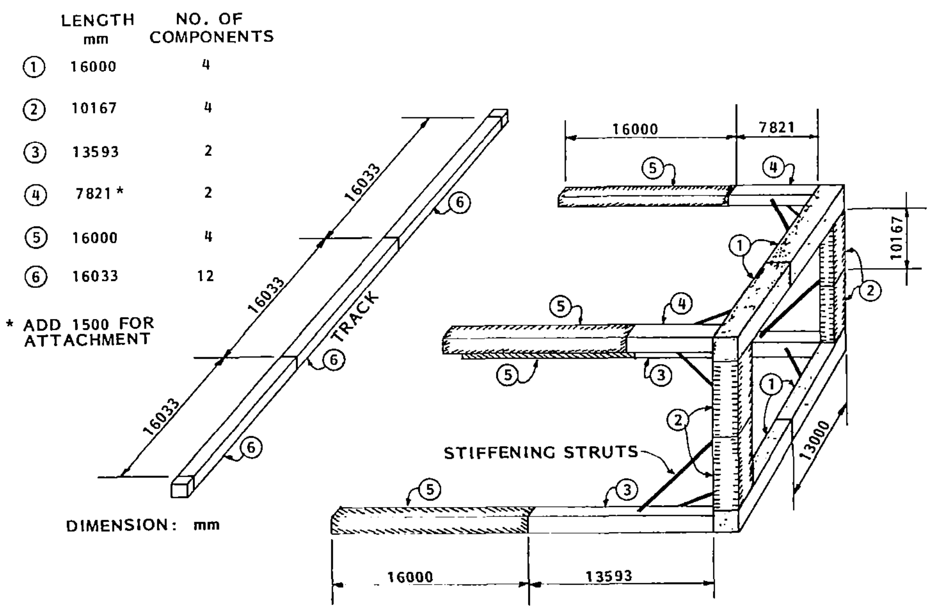


Figure A-19. Major Structural Elements.

Structural Elements

In order to permit stowing aboard the Space Shuttle, a collapsible design has been selected for the structural elements. The proposed system, based on experience with deployable mechanisms, is shown on Fig. A-20 for both conventional square cross section trusses and the track system. In formulating this design, it is assumed that structural members, made from composite materials with aluminum fittings, would be fabricated on the ground as flat panels of either truss or shear web construction. The maximum practical size of one panel to fit the constraints of the Space Shuttle cargo bay, appears to be about 1.5 meters wide x 16.0 meters long, so that the stowed dimension is about 3 meters x 16 meters (9.84 ft x 43.6 ft).

Using these panels, a beam is constructed by assembling four of them with spring hinges, as shown on Fig. A-20. In order to ensure stability in the deployed configuration, a number of folding diagonals are mounted along the span of the beam. These diagonals are driven by spring-loaded four-bar linkages which lock the elbows in the extended position. Finally, in order to increase the rigidty of the deployed beam, toggle locks may be used at intervals along the hinges to preload them and eliminate all free play.

Figure A-20 also shows the stowed configuration and the method of stacking these structural elements.

A similar approach is taken to fold the track elements, as shown on Fig. A-20. Spring-loaded hinges and appropriate toggle latches are used to assemble, deploy, and lock the three panels. The cross braces are hinged on one side. They are designed in such a manner that they can be released and secured after installation of the chains and drive mechanisms, prior to adjusting the chain tension. It is assumed that all locking operations will be performed manually by astronauts in EVA. This provides for required inspection to take place.

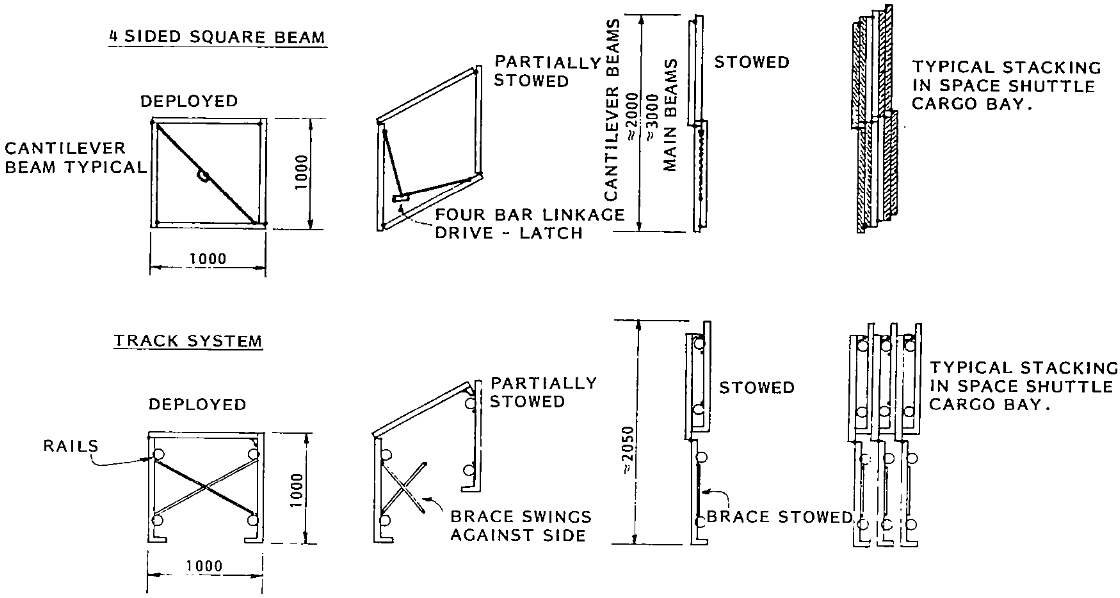


Figure A-20. Beam Stowage.

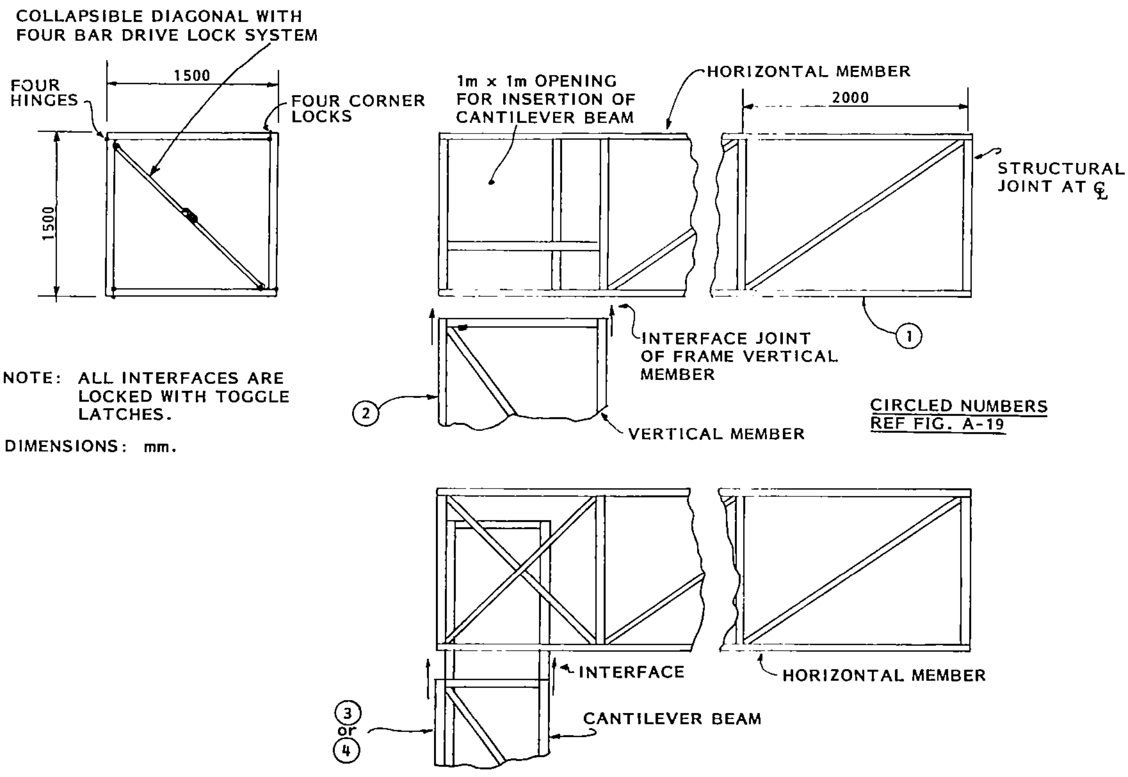


Figure A-21. Structural Details of Main Frame.

Release of the stowed beams for deployment should also be initiated by astronauts in EVA. A variety of mechanisms can be designed to ensure safe release from one single point at the end of the beam. For example, a spring loaded cable cutter may be activated to unlatch the stowing locks simultaneously. Hinge dampers may be used to slow the deployment motion to a reasonable rate.

Assembly of Structural Elements

The structural elements must be connected together in a manner that will ensure that the structure is continuous and rigid. This problem can be solved in a conventional manner by the use of shear connections and end load carrying latches. It will be necessary to provide some means of assisting the astronauts in locking elements together in a manner that does not require undue positioning precision. This can be achieved by appropriate design of the latches which can be set up to capture the interface and guide it into place when activated.

A2-4 STRUCTURAL DETAILS AND MECHANISMS

Main Structure

Preliminary layouts of the assembler structure are shown on Fig. A-21 to A-27. The main structure is examined first, referring to Fig. A-19 for the location of the element.

On Fig. A-21, a corner of the main frame consisting of elements (1), (2), and (3) or (4) is shown. The structure is shown as a typical Warren truss construction, although the stowing method allows the use of shear webs. It is assumed that shear webs would be used locally, wherever stiffness requirements are beyond the truss capabilities (e.g., at interfaces where concentrated loads are localized). The interfaces and associated mechanisms have not been detailed, except that cantilever beams (3) and (4) have a 1.5 meter extension to connect through beam (1), thus ensuring adequate rigidity of the junction.

Cantilever Beams

Figure A-22 shows details of cantilever beams, consisting of elements (3), (4), and (5). Note that elements (5) are common to both beams. They should be designed to be fully reversible, so that the tracks and RMS can be mounted on either face, thus making indexing unnecessary. A Warren truss type of construction seems adequate for this structure, although, as in the case of the quadrangle on Fig. A-20, local shear webs may be needed at some strategic locations; in particular, at the attachment of the stiffening struts shown on Fig. A-19.

Tracks

Figure A-23 shows a typical structure of the tracks, consisting of three No. 6 elements and two mechanism drive units. The basic frame is also the Warren truss type, with possible local shear webs at the interfaces. The crossbraces are shown as a tubular structure, but stiffness requirements may demand something more substantial. It is assumed that the rails would be made from stainless steel tubing, bolted to the uprights of the Warren truss. Aluminum alloy T-sections could be used for this purpose, but steel appears preferable for its smoother surface and better wear properties. Plug-in ends are considered as satisfactory rail connections between track elements and mechanism drive units.

Assembly of the tracks in orbit presents some particular problems. The following sequence of operation gives a general idea of one applicable procedure: (1) Three No. 6 elements, having been interconnected into a track, will be attached to the main frame cantilever beams. (2) The two mechanism drive units, chains and node retainer assemblies, will form a complete package.

(3) This package will be organized such that one mechanism drive unit can be separated without disconnecting the chains. (4) The other unit, including the set of five node retainer assemblies (on short rail extension), will be plugged at one end of the track, and secured. (5) The astronauts will then pull the chain and retainer assemblies along the track, either manually or with the assistance of suitable devices, until the other drive unit can be

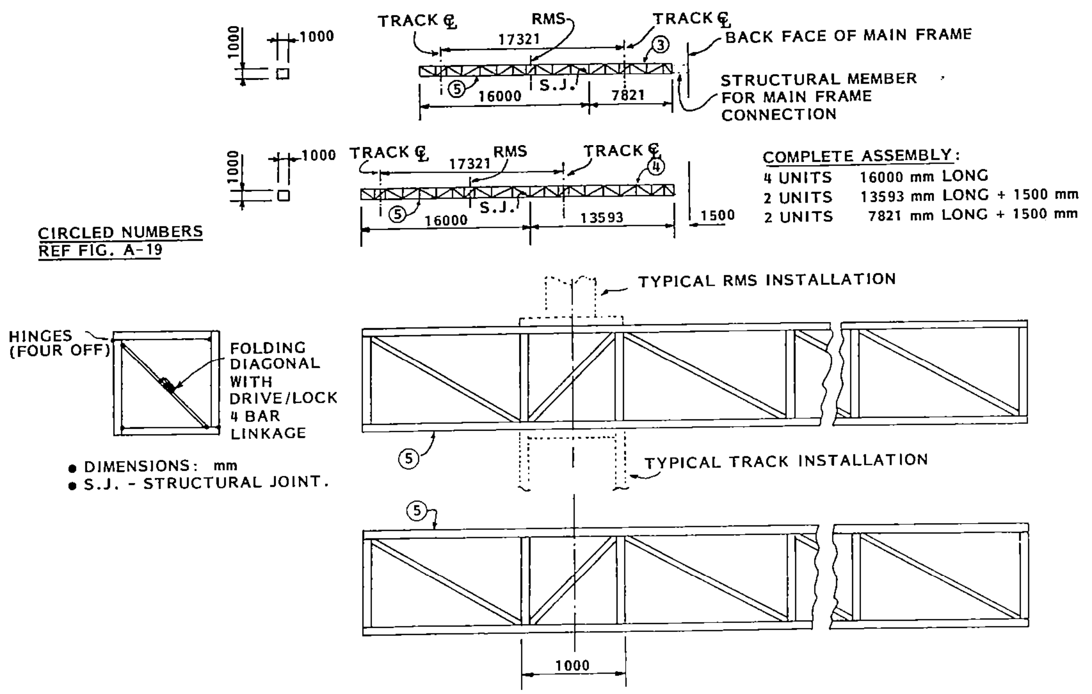


Figure A-22. Structural Details of Cantilever Beams.

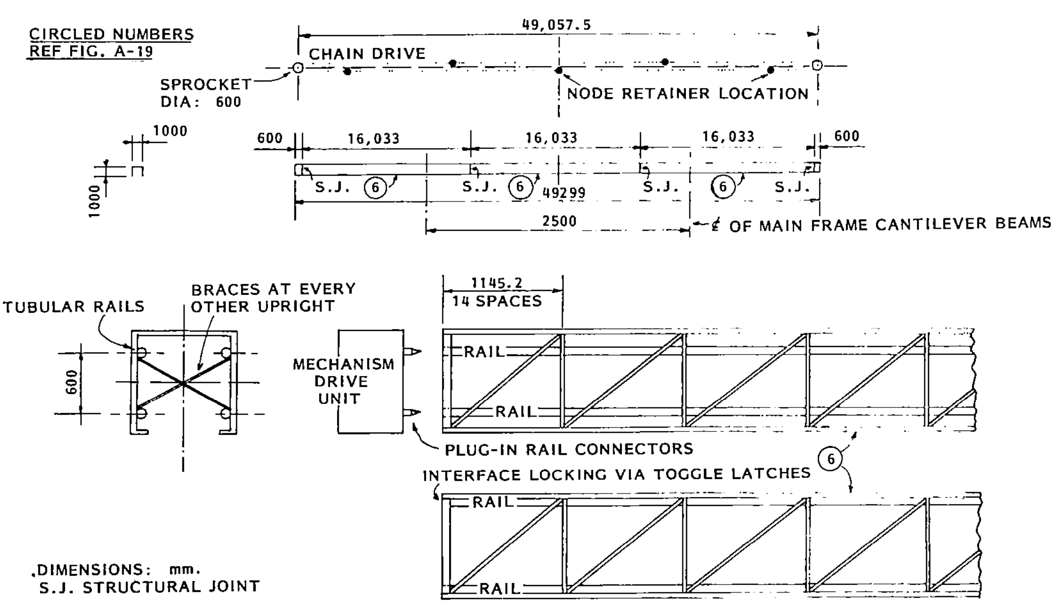


Figure A-23. Structural Details of Track.

plugged into the other end of the track. 6) The chain tensioning devices are then released, and to complete the assembly, the cross-braces are locked in place.

Track Ends and Node Distribution System

Figure A-24 shows a typical arrangement of the track end, with the node distribution system and the method of capture. The node retainers are provided with the capability of rotating 360 degrees about the shaft which links the rail slides. This feature was found necessary to perform the various motions required for the operation of the machine. Note that there is only one way for the retainer to enter the upper track. This requires that the retainer arm be in a trailing position. For exit, it must be in a leading position, as shown on Fig. A-24 for a left hand traverse. After capturing the upper track, the retainer arms must be rotated 180 degrees to be placed in a leading position. The consequence of this is that cross-braces cannot be used at each upright. These cross-braces must be separated by intervals sufficient to allow swinging the retainer arms from trailing to leading position. Furthermore, the motion of the chain drive cannot be continuous. It is necessary to place trip switches along the tracks at predetermined positions to stop the transit and allow sufficient time for swinging of the retainer arm. This can be combined with the track stop required for node capture, which is described below, as well as the mid-track stop, which provides precise node positioning for framework assembly.

As shown on Fig. A-24, the node fittings are provided to the track systems in canisters, one at each track end (eight canisters in all). These canisters are mounted on the tracks via toggle latches, easily removable for replacement. In these canisters, the node fittings are oriented in a fixed position. They are advanced one by one by a mechanism which must also bring them to the capture chamber without tripping any latches, which must remain open (e.g., node fittings of Section 4.1). The transport mechanism must also provide sufficient restraint to withstand the Space Shuttle launch environment. This system operates as follows:

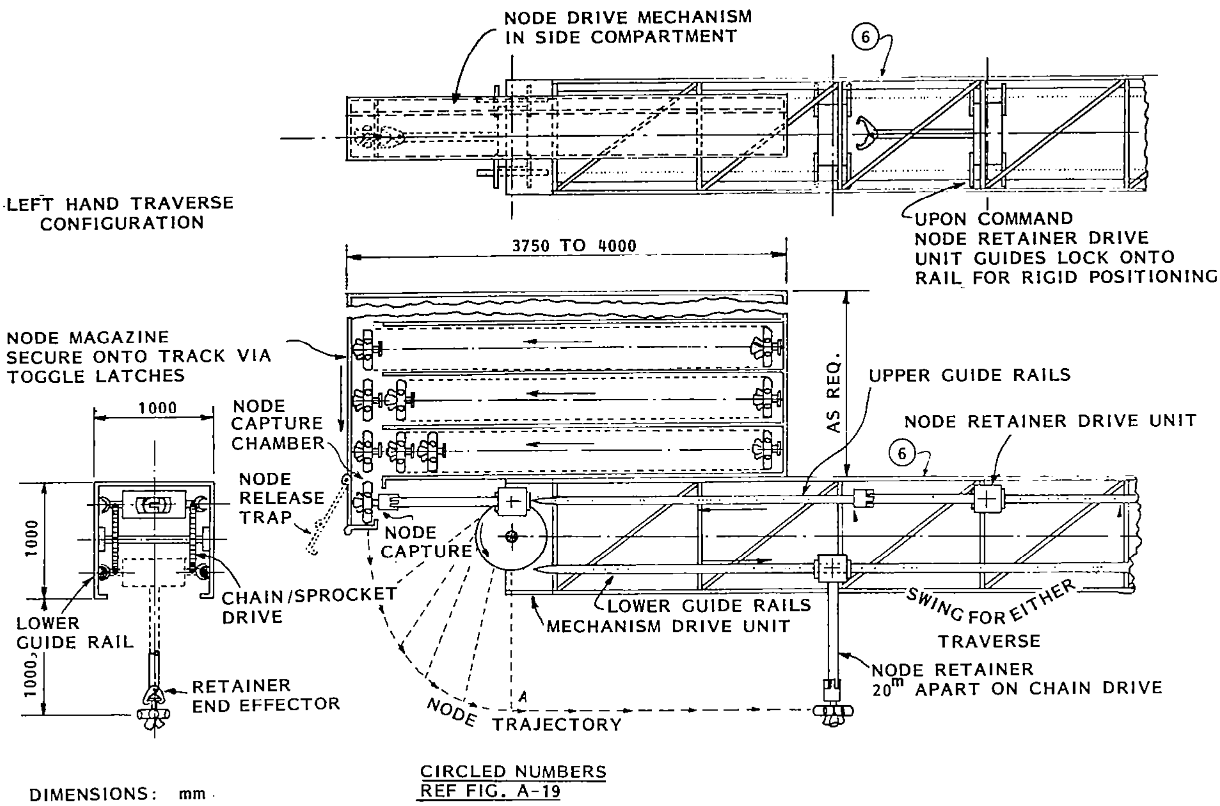


Figure A-24. End of Track.

a. A node is brought up into the capture chamber

b. The chain advances one node retainer with its end effector open

c. As the retainer end effector reaches the position of the node fitting head, a trip switch stops the chain drive and starts the following events:

(1) The end effector motor is activated to seize the node fitting

(2) The node release trap is opened

(3) Simultaneously, the chain drive is started and the node retainer arm is rotated 90 degrees (clockwise in the case of Fig. A-24)

(4) Another node fitting is advanced into the capture chamber

(5) The retainer arm is rotated to a specified angle to orient the node fitting as required for its position in the platform under construction.

The above sequence of operations forms a complete cycle which can be easily controlled automatically from the machine computer.

When the machine is traversing along the edge of a platform without performing assembly work, the above procedure is modified by simply not closing the retainer end effector, so that no node fitting is captured. Activation of the node release trap is also deleted and the end effector will automatically find itself lined up to seize a platform node fitting as it reaches point A (Fig. A-24) of its trajectory. This assembler progresses along the structure in a "hand-over-hand" fashion, getting hold of node fittings and releasing them as it goes.

Node Retainers and Drive Unit

Figures A-25 and A-26 describe schematically the mechanisms of the node retainers and their drive units. Five such units are required on each track (20 in all).

On Fig. A-25, the mechanism is mounted on a cross-shaft which spans between the two track rails. This shaft is fixed against rotation by the rail sliders shown in Fig. A-26. The system shown has four functions, all driven by electric motors. These functions are:

1. Rotation of the whole unit about the fixed shaft,
2. Locking of the unit against the track,
3. Orientation of the retainer end effector,
4. Operation of the retainer end effector.

All electrical motors are drive units, each consisting of two stepper motors and a reduction drive designed for emergency operation with one motor out. On Fig. A-25, functions 1, 3, and 4 have been shown with worm gear drives, which presents the advantages of minimum backlash and irreversibility.

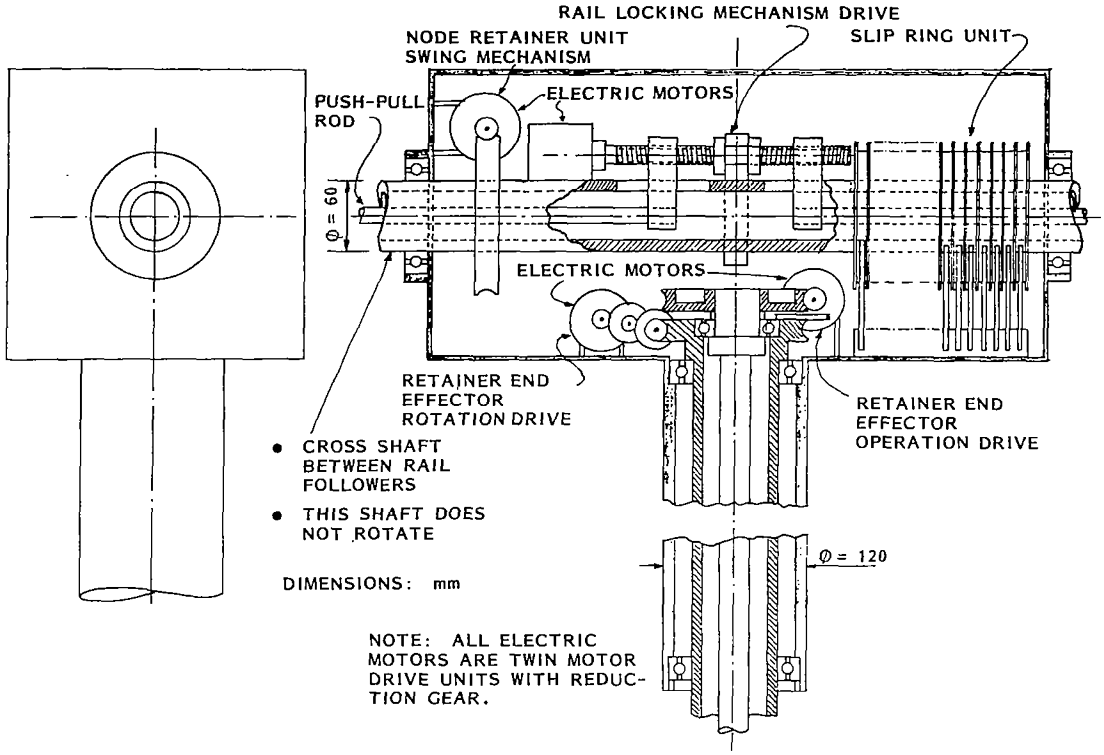


Figure A-25. Node Retainer Drive Unit.

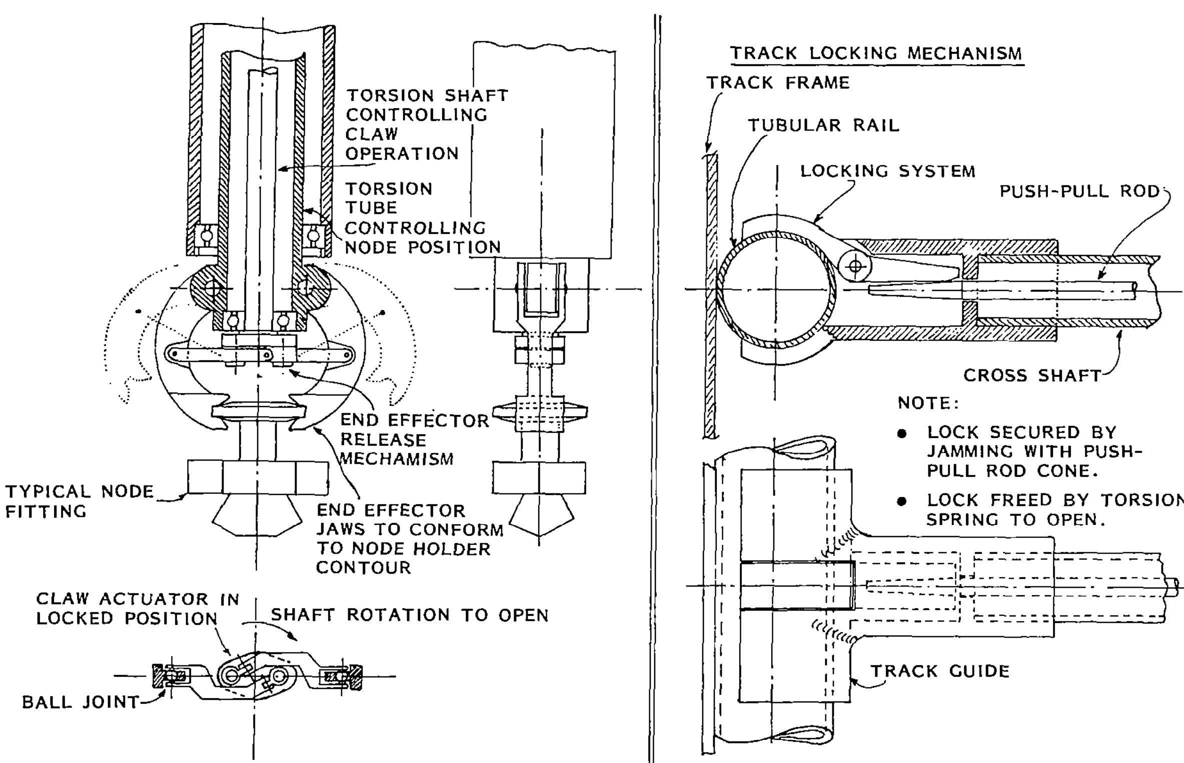


Figure A-26. Node Retainer End Effector.

Note that functions 3 and 4 must be integrated, either mechanically or electrically. Mechanical integration would require mounting the end effector motor on the end effector rotation shaft and using an additional slip ring to supply it with power.

For function No. 2, a simple cam system is used, which is powered with a mechanism based on the turnbuckle principle. The cam system which operates the clamp is shown on Fig. A-26. The track guide could be an aluminum casting and the lock a simple machined part normally held open by a spring.

The node retainer end effector is shown on Fig. A-26. A rotating shaft drive system was found preferable to a push-pull rod and associated scissor mechanism as the proposed configuration is more compact and has better mechanical advantage in the closed position. The end effector profile is designed to allow fairly large position tolerances in getting hold of the node fitting head. The double cone head ensures tight gripping by the claw.

A block of slip rings is shown on Fig. A-25. This is necessary since the mechanism must be capable of rotating one complete revolution for each track cycle. Current and control signals are transmitted to these slip rings through the hollow shaft from a harness which runs along one of the drive chains. The harness itself is supplied from slip rings connected to the driving sprockets.

Note that the shape and dimensions of the housing shown on Fig. A-25 are only schematic. In a final design, the box can be extended in the direction of the retainer arm, if additional internal space is needed.

Interchangeability of the units can be performed when they are located on the chain sprocket at the low position, with the retainer arm directed downward (see Fig. A-24). In this position, any unit may be separated from the chain by disconnecting the harness and operating the latches which secure it. Replacement of a defective unit or changeover to units having different

features (such as special end effectors) may be performed quickly without unduly disturbing the machine.

Column Storage and Distribution

A typical arrangement which may be used when the columns are supplied completely assembled is shown on Fig. A-27. This assumes that column assembly is performed separately from the machine by an appropriate piece of equipment which extracts half-columns from the "stacked" packaging and connects them together. These columns would then be taken to the assembler and loaded in the canister shown on Fig. A-27. This canister, which is in two parts, is equipped with a system of chain drives which advance the columns one-by-one to a pick-up position. The assembler insertion mechanisms grab the column by both ends and pull it off the canister retainer. A system of guides will ensure that the insertion mechanism end effectors will always grab the columns at a fixed distance from its ends and over a suitably reinforced section of the end fittings. This will prevent damaging the thin graphite shell and will ensure correct positioning of the column in the platform under construction.

Another option under consideration consists of "double plastic cup" stacked columns having a hinge at their center section (described in Section B-2). This configuration would feature self-powered hinges and a four-bar linkage lockup system. In this case, canisters containing stacks of folded columns could be supplied directly to the assembler, where a device would extract them set-by-set, let them deploy and lock under their own spring power, then position them for RMS capture.

Robotic Handling Devices

At this time, no special study was performed to define the characteristics of the handling and insertion devices required on this assembler.

In general, the work done in this study provides a basis for some of the requirements which must be met by these insertion mechanisms.

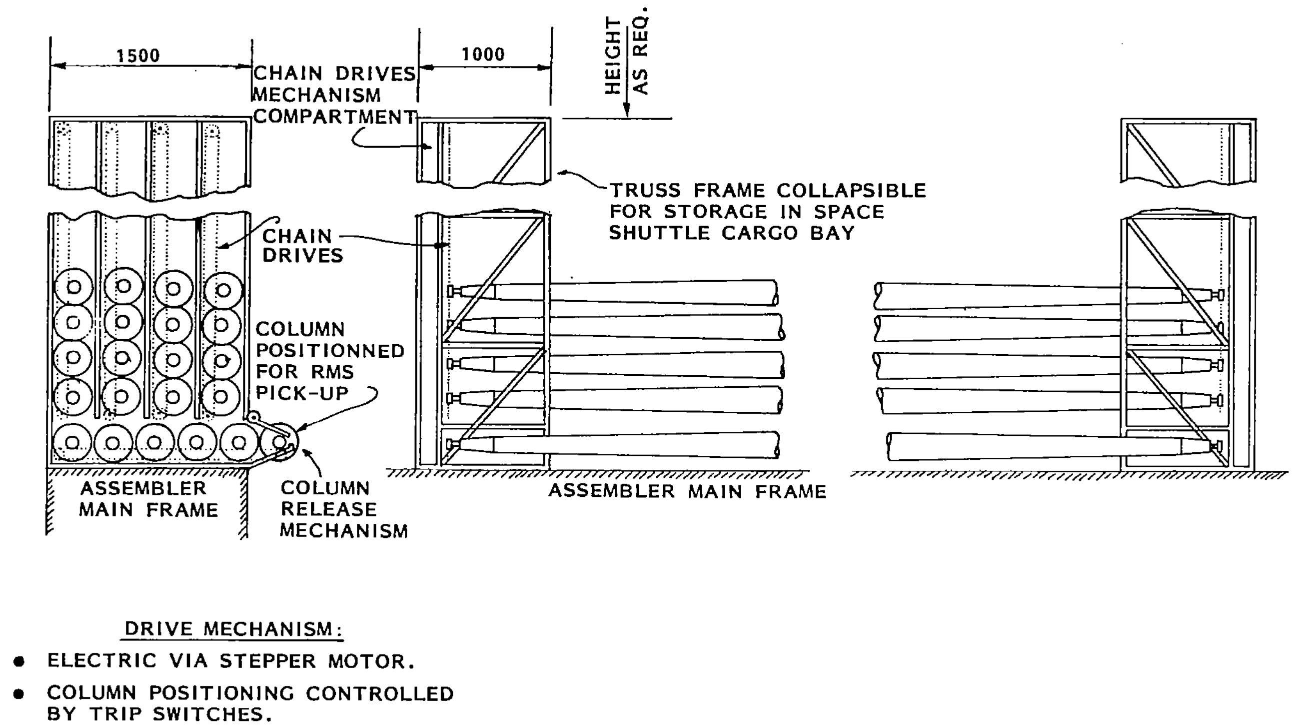


Figure A-27. Column Storage and Distribution.

a. Continuous operation over a long period of time.

b. Mechanical redundancy to prevent frequent breakdowns.

c. Ease of replacement. (They are mounted externally on the assembler for this purpose).

d. Capability to transport a column from the distributor to its location within the platform in one minute or less.

e. Capability to follow, under computer control, a prescribed trajectory in a (x, y, z) coordinate system.

f. Acceleration limiters may be required to minimize dynamic interactions.

g. Multiple duty end effectors will be needed as most node joint designs require means of applying a preload to the clamping mechanism.

h. Position precision ±13 mm (±0.5 in.) in all axis.

Crew/Computer Compartment

Accommodation for a crew of at least two astronauts, and a computer compartment, must be installed in a position such that the crew can have a good view of the work being performed within the operation quadrangle. This problem has not been addressed in any details in this study but the general layout has been conceived and its implementation would not present any undue difficulties.

Power Supply

The energy requirements have not been estimated. This machine, however, should be made as self-sufficient as possible. The installation of large deployable/retractable solar arrays is under consideration.

A2-5 ASSEMBLER OPERATIONAL PROCEDURE

Column Insertion Mechanism Operation

By design, the robotic devices are intended for operation within the volume defined by the four cantilever beams and the four tracks. Since they must work in pairs, each holding one end of a column, they cannot insert any structure outside of this volume, since one insertion mechanism would not reach far enough.

Under computer control, the insertion mechanism will pick up a column from the storage-distributor, and orient it so that each end follows prescribed trajectories which will terminate at the coordinates of the appropriate node fittings. At this point in the motion, the column joints will be inserted into their respective fittings and locked in place, either automatically or under the action of special devices mounted on the end effector.

With four devices operating in pairs (two upper and two lower), two columns can be mounted simultaneously. Insertion mechanism operational times are tentatively set as follows;

Column pick-up:	10 seconds
Column transit:	60 seconds (max, trajectory case)
Column lock-up:	15 seconds
Insertion mechanism return to pick-up:	30 seconds
Total	115 seconds

Therefore, two columns can be set in approximately two minutes, but three columns will require four minutes, since one RMS set must remain idle. Thus, the insertion mechanism operational time can be tabulated as follows:

No. of Columns	Installation Time - Min
1 or 2	2
3 or 4	4
5 or 6	6
n or n+1	n+1

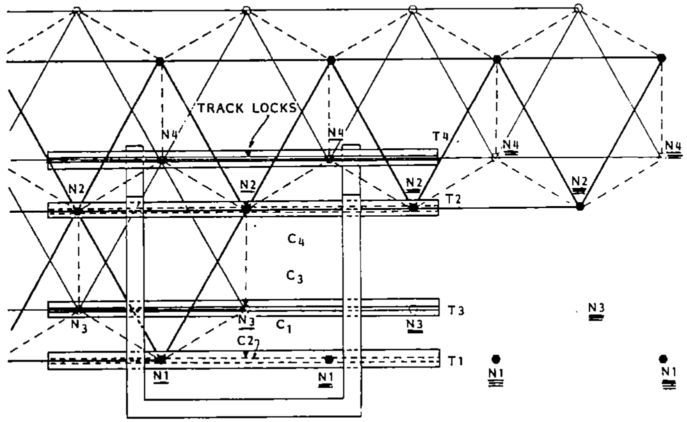
Assembler Operation - Traverses

Figure A-28 shows schematically the assembler configuration at the beginning of one cycle of a right hand traverse. The tracks are equipped with controlled locks placed exactly half-way between the two cantilever beams. The purpose of these locks is to provide precise positioning of the machine with respect to the platform under construction. It can be seen that the motion can proceed only in steps of 10 meters. In the example shown on Fig. A-28, node retainers holding N2 and N3 are secured against the locks of tracks T2 and T3. In the next traverse step, it is the retainers holding nodes N4 and N1 which will be secured by the locks of tracks T4 and T1. These locks are released by electromechanical devices. They are of a double locking type designed to be effective for either right or left hand traverse.

Right Hand Traverse

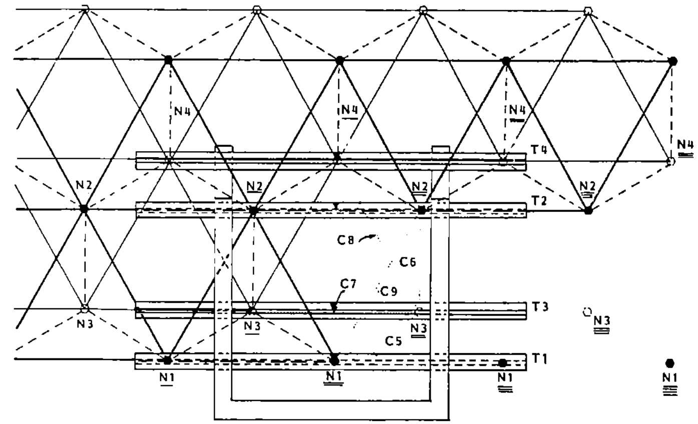
STEP 1. In the configuration on Fig. A-28, the assembler is connected to the platform under construction at eight nodes: N1, N2, N2, N2, N3, N3, N4 and N4. Two nodes have been secured from the node canisters at the right hand side of track T1 and T3 (nodes N1 and N3). However, only node N1 is within the operational volume. Therefore, the RMS has the capability of inserting four columns: C1, C2, C3, and C4.

Columns C1 and C4 will be inserted by the lower insertion mechanism and C2 and C3 by the upper insertion mechanism. In order to prevent placing additional obstruction in the path of the working insertion mechanism, the oblique columns (i.e., those connecting the upper and lower planes of the platform) should be placed first. In this case, the lower insertion mechanisums should install column C1 first. For the same reason, the upper insertion mechanism should install column C2 first, as column C3 might restrict its access to node N1. The operational time for this step is: transit = zero, work = four minutes, for a total of four minutes.



- USE MANIPULATORS TO INSERT COLUMNS IN THE ORDER SHOWN: C1, C2, C3 AND C4.
- UNLOCK TRACK-LOCKS AT N2 AND N3 IN READINESS FOR NEXT TRAVERSE STEP.

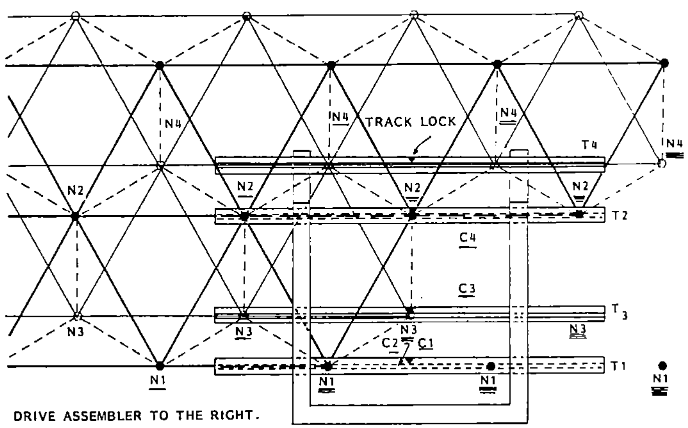
(A)



- DRIVE ASSEMBLER TO THE RIGHT.
- RELEASE NODES N2 AND N3.
- CAPTURE NODE N4 IN RETAINER.
- CATCH NODE N1 FROM LOADER.
- CAPTURE NODE RETAINERS N1 AND N4 IN TRACK-LOCKS.
- USE MANIPULATORS TO INSERT COLUMNS IN THE ORDER SHOWN: C5, C6, C7, C8 AND C9.
- UNLOCK TRACK-LOCKS AT N1 AND N4 IN READINESS FOR NEXT TRAVERSE STEP.

(B)

STEP NO. 2

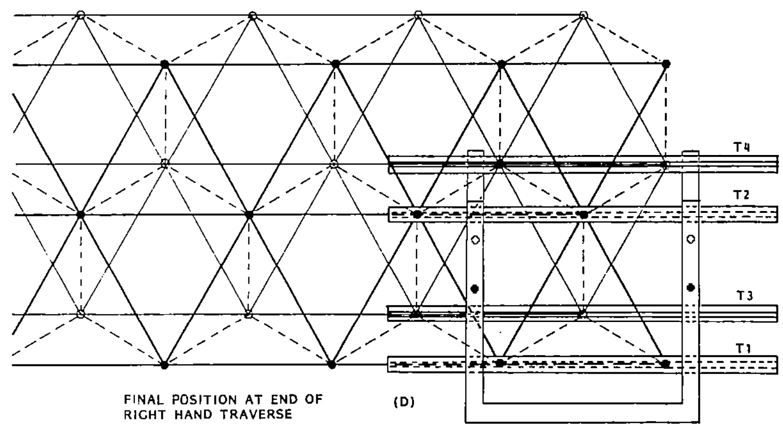


- DRIVE ASSEMBLER TO THE RIGHT.
- CATCH NODE N3 FROM LOADER.
- CAPTURE NODE N2 IN RETAINER.
- CAPTURE NODE RETAINERS N2 AND N3 IN TRACK-LOCKS.
- REPEAT STEP 1 AFTER PERFORMING A 10m TRANSIT TO THE RIGHT.

(C)

STEP 3

REPEAT CYCLE



FINAL POSITION AT END OF RIGHT HAND TRAVERSE

(D)

Figure A-28. Right Hand Traverse.

STEP 2. Figure A-28 shows the new configuration after the assembler has been driven one 10 meter step toward the right. In view of the operations which the track must perform to release and capture nodes, secure new nodes from the canister, the transit time must be relatively low. Slow motion is also a requirement, in order to prevent accelerations detrimental to the system from the standpoint of loads, structural and orbital stability. It is considered that with careful monitoring of the start-stop transient accelerations, a mean transit velocity of 0.10 m/sec can be taken as a reasonable estimate. Therefore, the transit time would be on the order of two minutes per 10 meter step.

In the configuration on Fig. A-28, the assembler and the framework are again connected by eight nodes: N1, N1, N2, N2, N3, N4, N4, and N4. Nodes N2 and N3 have been released and node N4 has been captured, while node N1 has been secured from the canister. Node N3 has now moved within the operational volume and five new columns may be inserted. The lower RMS will install columns in the order C7, C6, C8, while the upper insertion mechanism will install C5, then C9.

The total operational time for this assembly is two minutes transit plus six minutes work, or eight minutes total.

STEP 3. This step will complete one traverse cycle. The assembler traverses toward the right another 10 meters, to the configuration shown on Fig. A-28. In so doing, it releases nodes N1 and N4 and captures node N2, while securing node N3 from track T3 canister. The machine and the frame work are again connected at eight points: N1, N2, N2, N2, N3, N3, N4, and N4, while the new node to be connected to is N1.

Following the now familiar sequence, the lower insertion mechanism will insert columns C1 and C4; the upper insertion mechanism, columns C2 and C3.

After performing another 10 meter transit to the right, the configuration becomes identical to that of Fig. A-28, thereby starting a new cycle.

The total operational time for this step is initial transit = two minutes, work = four minutes, final transit = two minutes; or eight minutes total.

The total time required to perform one cycle of a right hand or left hand traverse is approximately: 4 + 8 + 8 = 20 minutes, during which 4 + 5 + 4 = 13 columns are added to the framework.

The average time to insert a column is approximately 1.54 minutes (92.3 seconds).

Summary of Traverse Operational Time - One Cycle

The operational times for one cycle of either right of left hand traverse are summarized in the following table.

Traverse Step	Transit min	Work min	Total min	No. Columns Inserted
1	0	4	4	4
2	2	6	8	5
3	2+2	4	8	4
Totals	6	14	20	13

Average column insertion time: approx 1.54 min

Assembler Operations - Row Change

Once the assembler has reached the end of a row, it must be moved one step crosswise to be reconnected to the framework in position to start an opposite hand traverse. The performance of this motion is greatly simplified in this machine, since it can be accomplished by use of the insertion mechanism, under constant computer control. The use of a feedback control system monitoring

the motions of both machine and framework should provide a safe method of handling this operation.

Figure A-28 shows the machine/framework configuration at the end of a right hand traverse. It is necessary to move the assembler to a new position, where tracks T2 and T4 will be connected to nodes of the lines presently held by tracks T1 and T3.

In order to separate the two units, the insertion mechanism will be connected to the cylindrical shafts of the node fitting heads, but the configuration on Fig. A-28 is not suitable as the node positions are not equally balanced about the machine axis. It is necessary to transit one step to the left in order to obtain a favorable geometry. This is shown on Fig. A-29 (time required, two minutes). On Figure A-29, the upper insertion mechanisms are connected to nodes N1 and N1; the lower insertion mechanism to nodes N3 and N3. In both cases, the insertion mechanism end effectors lie in planes parallel to that of the platform upper and lower surfaces. This is necessary as these end effectors will have to rotate 180 degrees about their respective nodes during the transit. Once the end effectors have been secured, all node retainers (three each on T1 and T4, two each on T2 and T3) are disconnected from the nodes and retracted by swinging 90 degrees in-line with the chain drives. This provides a clearance of $\pm$ one meter between the machine and the framework.

The time required to perform the above operations under computer control should not exceed five minutes. Another five minutes may be used by the astronauts to verify that all manipulators are properly secured on their nodes; i.e., 10 minutes total for this phase.

Cross transit is shown on Fig. A-29, at mid-point during the translation. The end effectors should be provided with Triax accelerometers whose output, fed to the computer, would be continuously monitored to control the relative motion between the two bodies, which are effectively performing a controlled separation. This feedback control technique should be effective in preventing unwanted motions and possible collisions. The translation velocity must

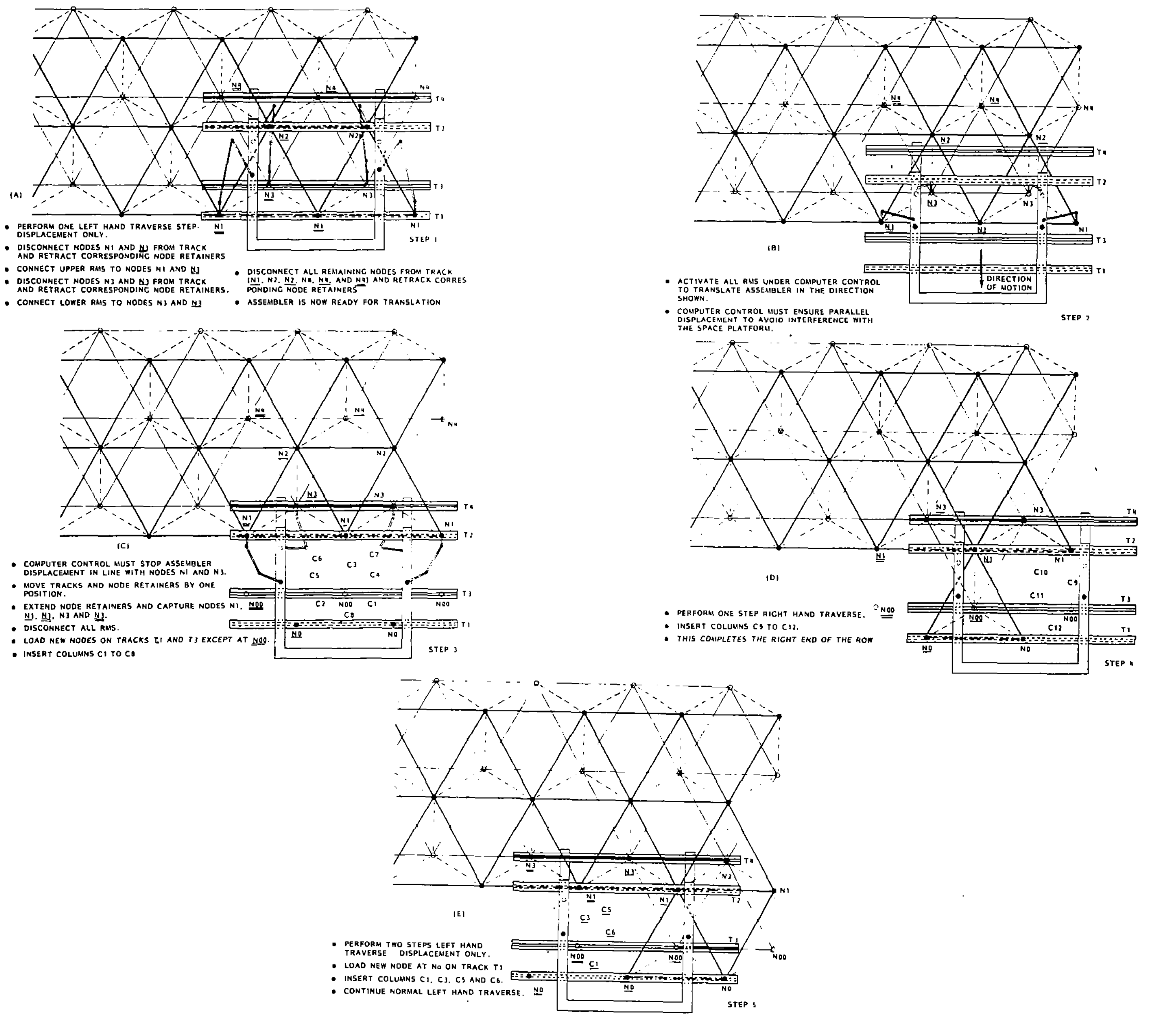


Figure A-29 Schematic of Motion Study.

remain low so that start/stop operations can be performed by astronauts overriding the computer without introducing large transient accelerations. It is anticipated that a velocity of 0.02 m/sec will be satisfactory. This corresponds to a transit time of about 15 minutes to cover a distance of 17.32 meters.

The general configuration at the end of the cross-transit is shown on Fig. A-29. The end effectors under computer control have realigned the machine and framework to match coordinates at tracks T2 and T4. Tracks T2 and T4 must be moved one 10 meter step to realign the node retainers with the new node position. Tracks T1 and T3 must be stepped several times, capturing from the canisters nodes NO, NO, NOO, and NOO, (but not NOO) at this time. This can be accomplished during transit; therefore, no time need be budgeted for it.

Following the procedure described earlier in the traverse method of assembly, the mechanism will insert columns C1 to C8 as shown on Fig. A-29C (time required, nine minutes).

Before starting the standard left hand transit, it is necessary to complete the right hand edge of the framework by stepping right one 10 meter step, which allows insertion of columns C9 to C12 (Fig. A-29): transit time, two minutes; work time, four minutes; total time, six minutes.

The standard left hand traverse can now be started by performing two transit steps to the left, securing from the node canisters nodes NO and NOO. At this position, shown on Fig. A-29, the normal left hand traverse begins its first cycle. Columns C1, C3, C5, and C6 may be inserted.

For time accounting purposes only, transit time in this phase is considered to remain consistent with the definition of the traverse. Two 10 meter traverse steps without performing work require 2 x 2 = 4 minutes.

Summing up the times required for each phase of the row change gives the following table:

Phase		Transit Time min	Work Time min	No. Columns Inserted
1	One step left hand traverse	2	0	0
2	Setting manipulators and verifying	0	10	0
3	Cross transit	15	0	0
4	Realign node retainers	0	0	0
5	Reconnect node retainers - insert eight columns	0	8	8
6	One step right - insert four columns	2	4	4
7	Two steps left - ready for left hand traverse	4	0	0
	TOTAL	23	22	12

45 min

The row change can be accomplished in about 45 minutes, during which 12 columns are inserted before the next opposite traverse can proceed.

Summary of Operational Times

The operational times are summarized below as a convenient reference for both traverse and row change.

Operation	Transit Time min	Work Time min	Total Time min	No. Columns Inserted
One cycle traverse	6	14	20	13
Row change	23	22	45	12

The above data provides a means of determining the time required for the assembly of a specified platform. Note, however, that it will be a function of the size and geometry of the platform. On a small platform, the proportion of time taken to perform row changes will be more significant than on a large one, where the row change frequency is reduced.

The operational times have been selected in a rather conservative manner for the purpose of minimizing dynamic reactions on the assembler and the framework under construction. Faster operation is most likely possible. This, however, requires a dynamic analysis of the motion to determine elastic deformations and their effect on positioning accuracy, upon which the system is dependent.

It is believed that a very high construction speed is not an absolute necessity, as it is dependent on the rate at which supplies can be brought up by the Space Shuttle. Considering a 2700 column load per flight, a nominal flight rotation of 14 days, and assuming a total average column insertion time of two minutes, the whole load would be assembled in 5400 minutes (i.e., 90 hours, or 2 x 45 hour weeks). This appears to be a reasonably feasible schedule.

A2-6 GENERAL REMARKS

Television Cameras

Television cameras should be provided to help the astronauts in supervising the operation of this machine. Four cameras, on power gimbals, could be

mounted on the vertical faces of the cantilever beams, adjacent to the insertion mechanism mounts and inside the working quadrangle. Each camera control could be normally coupled with the insertion mechanism in order to keep the mechanism end effector in sight. Overriding controls should be provided as well, for astronaut convenience.

Work Schedule

Loading the machine with a full Space Shuttle load of columns (2700) does not appear feasible because of its bulk. The number of columns which can be housed in a distributor of the type shown on Fig. A-27 is approximately 100; or 200 total. It is noted that 2700 columns installed in two weeks of five days work is equal to 270 columns per day, or 135 columns for each distributor. This number appears feasible; thus, daily loading from a nearby supply would be required. The time required to remove the empty distributors and substitute loaded units is difficult to assess, as it will depend on the proximity of the supply and the method of transfer. It is assumed that, with a well optimized system, this substitution can be performed in about one half hour, or six hours for each Space Shuttle load.

Node Fittings

Substitution of node canisters is a simpler problem which need be performed only once for each Space Shuttle load. The number of nodes corresponding to 2700 columns is in the order of 600 to 650. Since the node joints are small items, each canister may have a relatively large capacity. One hundred appears quite feasible within a reasonable volume. A full complement would be some 800 nodes; sufficient for one Shuttle flight, or 2700 columns. Note that the number of available node joints must be somewhat greater than the requirements, since the machine will run out of columns in a traverse not necessarily correlated with the availability of nodes. A surplus is necessary so that the supply of columns can be used up. Furthermore, note that the greatest node distribution rate occurs from tracks T1 and T3. Therefore, canister design should be optimized to avoid more than one reloading for each Shuttle cycle.

Half-Column Assembly

The two preceding remarks imply that assembly of half-columns into complete columns must be performed separately from the platform assembly. Thought has been given to this problem and a suitable procedure has been determined as follows.

A separate machine would connect the half-columns together. Such a machine is described in Appendix B. Conceivably, this machine could be part of the Space Shuttle package which would be unloaded in one bulk. This machine would then move clear from the Space Shuttle, start connecting half-columns into complete columns and store them in an empty distributor. This distributor will then be taken to the assembler where the insertion mechanisms will position it on the main frame. Meanwhile, the column machine would fill up another distributor. Platform assembly could then proceed as soon as two loaded distributors have been set. Empty distributors can be taken to the column machine for reloading on a daily basis. In the meantime, the Space Shuttle will load one empty column/machine package and return to base.

Thermal Expansion

Thermal stability of the assembly machine and fabricated space structure was examined briefly by considering the total thermal expansion of one 20 meter column. Such a column has a total length of 787.4 inches (20 m), which consists of about 10.5 inches (28 cm) of aluminum and 776.9 inches (19.72 meters) of graphite/epoxy. The coefficients of thermal expansion are respectively:

Aluminum	$+13\ \mu\epsilon/^\circ F$ ($23.4\ \mu\epsilon/^\circ C$)
Graphite epoxy	$-0.20\ \mu\epsilon/^\circ F$ ($-0.36\ \mu\epsilon/^\circ C$)

Therefore, the aluminum will expand by 1.365×10^{-4} in./°F (6.239 m/°C) and the graphite epoxy: = -1.5538×10^{-4} in./°F (-7.104 m/°C). Thus, the total change in length is a slight contraction of -1.888×10^{-5} in./°F (-0.853 m/°C). This is clearly not significant and the columns can be considered as practically thermally stable.

From this, it is concluded that the structure of the assembler should also be built of an aluminum alloy-graphite/epoxy combination to match the above platform structure thermal characteristics.

Conclusion

The Space Platform assembler presented in this section provides an automatic method of constructing these large structures. Its technology is based on LMSC experience with satellite mechanisms. It requires the design of a specialized heavy-duty insertion mechanism, which is the working arm of this machine. In compiling this document, care has been taken to insure that solutions exist for the problems associated with the machine concept, stowage in the Space Shuttle, erection in orbit, and operation in orbit. It is concluded that fabrication of this machine should not present unresolvable problems.

Construction time appears to match the Space Shuttle turnaround schedule on the basis of the assumptions made regarding the insertion mechanism operational speed requirements.

This machine is designed to allow only light operating loads in order to reduce elastic deformations to a practical minimum. Nevertheless, a dynamic analysis is required to determine the system responses to operational loads. It is assumed that a construction which involves a combination of aluminum alloy and graphite/epoxy can be made thermally stable by judicious design, since graphite/epoxy has a negative coefficient of thermal expansion. The virtual absence of thermal distortion is a significant advantage in maintaining the position precision required for such large assemblies.

APPENDIX B

AUXILIARY COLUMN ASSEMBLY DEVICES

This appendix presents first a survey of various techniques which may be used to connect the half-columns together. This trade-off study considers the kinematic requirements of a variety of configurations using either separate or hinged half-columns. In evaluating the results of this study, it should be noted that the mechanical complexity of the drive system was not a prime consideration at this early conceptual stage. A more advanced study is needed to resolve this problem and provide a sound foundation for selection of the most appropriate system.

The second part of this Appendix describes a type of self-deployable folded column which can be stowed compactly in plastic cup fashion. When extracted large-ends-first from a canister, they automatically deploy and snap-lock in the open position. Such a technique presents a number of advantages over the separate half-columns, especially when considered for off-site assembly where ample space is available.

Part 3 deals with the off-site assembly of half-columns using either self-deployable or two part columns in a special free flying installation loading the completed columns in larger canisters for transport to the assembly machine.

Although the mechanisms presented in this Appendix were generally not retained as part of the selected configuration, they are of interest as they may lead to future developments.

B-1 HALF-COLUMN ASSEMBLY STUDY

This section presents a study of the methods which can be used to assemble the half-columns into complete columns. To connect two half-columns, it is necessary to extract them from the supply canisters, manipulate them to orient them

head-to-head, rotate them to set their index marks, and snap them together under a preload until locked. This sequence of operations can be performed in different manners, depending on the configuration of the canisters, space available for handling the half-columns, and tolerable mechanical complexity. Eight schemes were devised, and the simplest of them was examined in some detail. The mechanism which captures, rotates, and snap-fits the half-columns is defined in Section 5.3. Generally, it is common to any one of the eight schemes. Electric stepper motors are recommended to power all functions of this assembly.

Half-Column Assembly Schemes

Basically, the manipulations required to extract the half-columns from the canister and assemble them will consist of either translations, lateral and axial, or translations combined with rotations. In addition, indexing requires rolling of both half-columns. Figure B-1 presents eight different schemes by which the required motion can be performed. Four schemes (1, 4, 5, 6, 7 and 8) involve only translation, and two schemes (2 and 3) involve both translation and rotation. In all cases, roll-indexing is a separate motion.

Description of Scheme No. 1, Fig. B-1

In this scheme, two canisters are placed in reversed positions so that columns can be extracted toward the right and toward the left as shown on Fig. B-1. The required translations follow the path marked 1, 2, 3 symmetrically for each column. At position 4, the two half-columns, which are facing each other, are indexed and connected. The completed column is then transported toward its location in the platform under construction, or toward temporary storage in a special canister. As shown on Fig. B-1, the space requirement for this scheme is 37 meters with the 17 meter wide canisters placed in the middle. Special canister design is required to unload the stacked columns laterally.

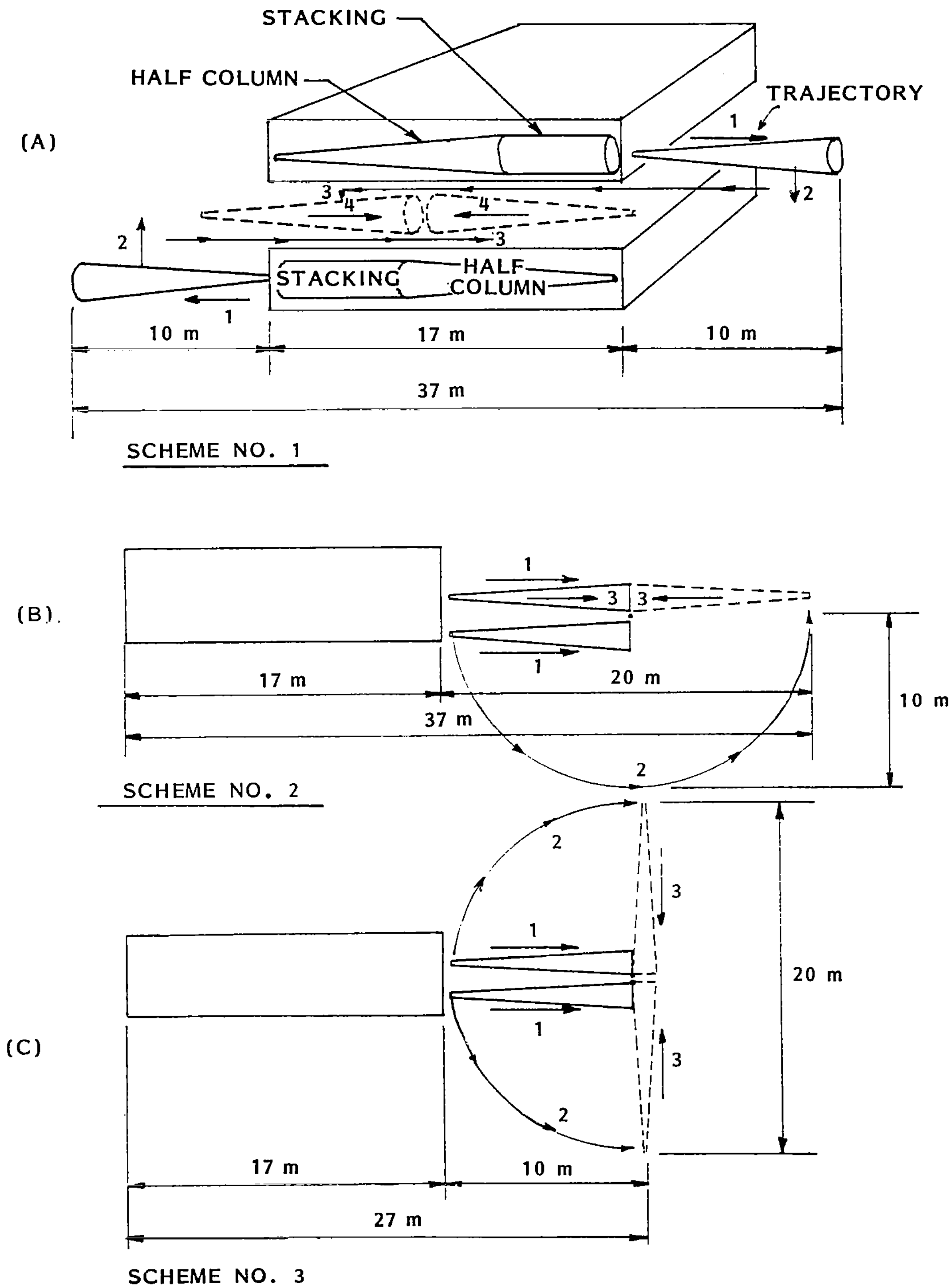
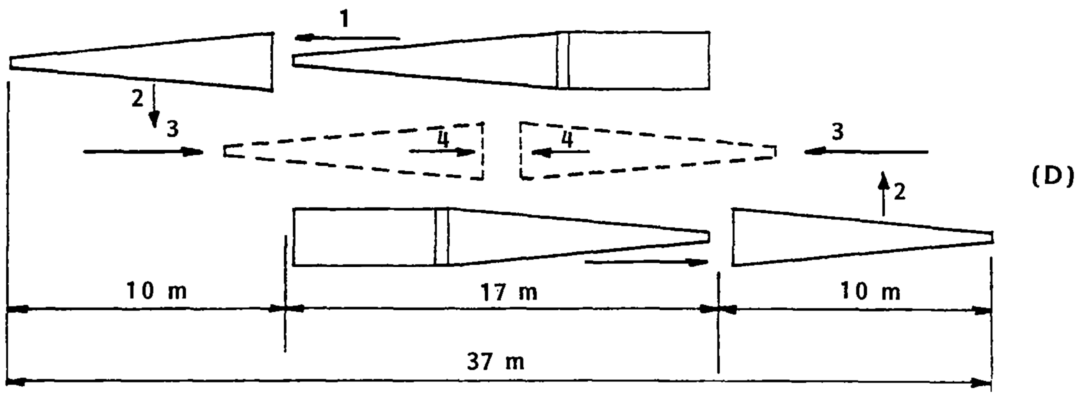


Figure B-1. Half-Column Assembly Schemes.



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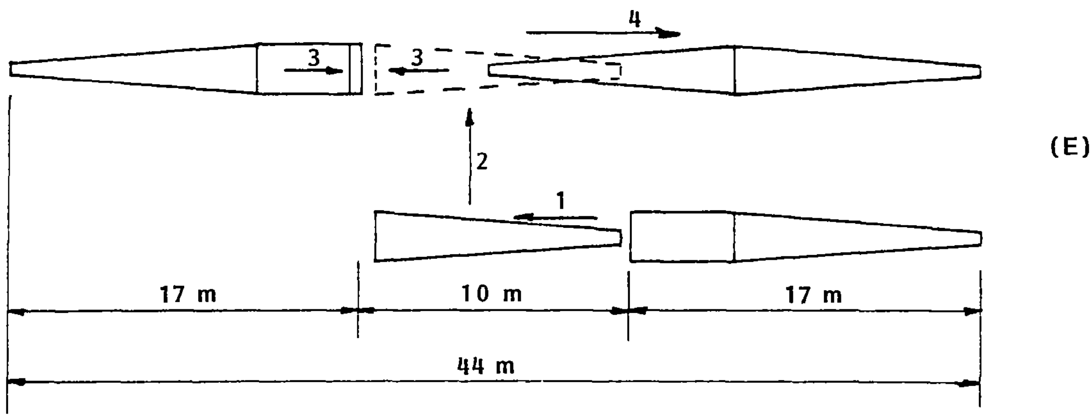

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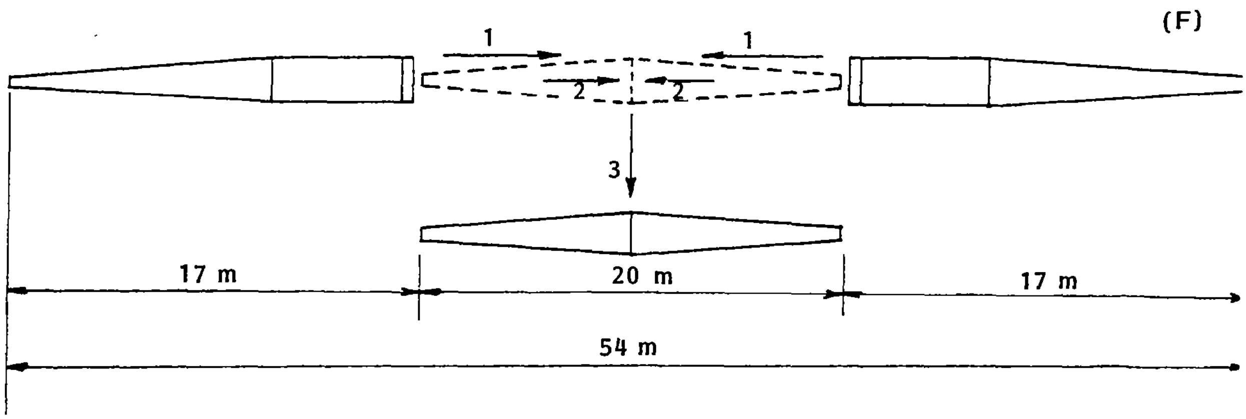
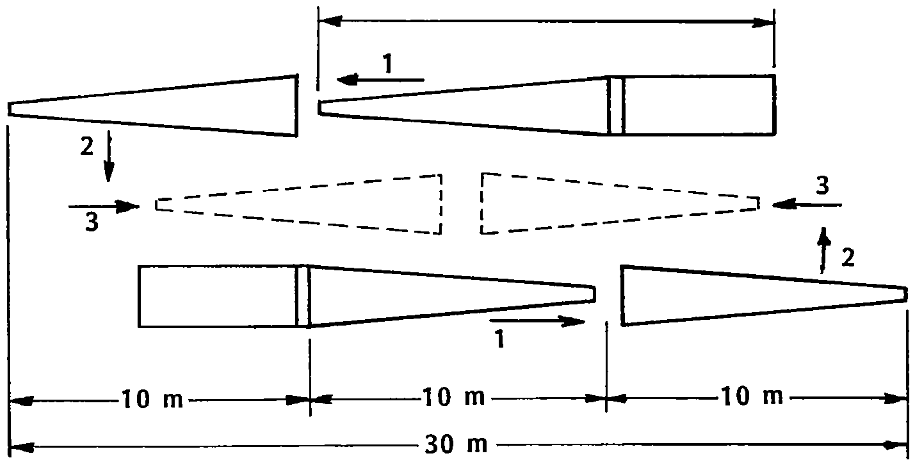
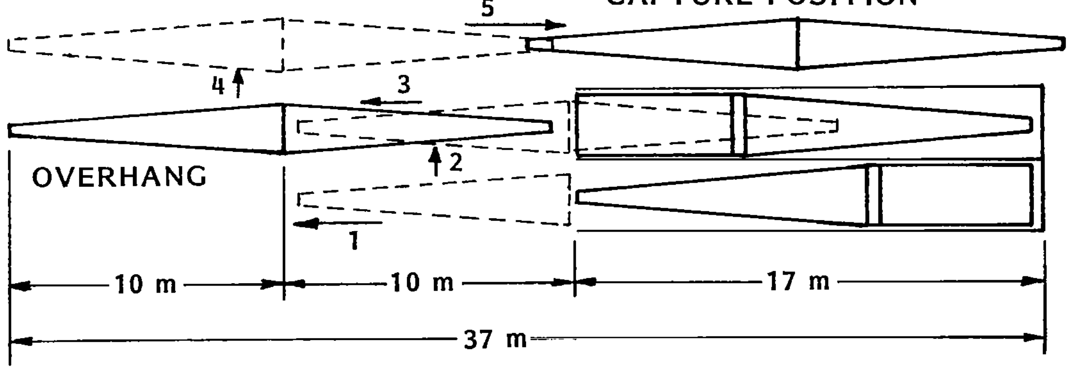


SCHEME NO. 6

Figure B-1. Half-Column Assembly Schemes (Continued).



SCHEME NO. 7



SCHEME NO. 8

Figure B-1. Half-Column Assembly Schemes (Concluded).

Description of Scheme No. 2, Fig. B-1

This scheme is a combination of translation and rotation which is used to minimize the motion requirements and simplify the needed mechanism. The half-column canisters are used in pairs side by side or alternately contain two rows of stacked columns. These column stacks are moved out by a mechanism which locates one set of two half-columns in the capture area, where another device will clamp itself on the large end fittings. The half-columns are withdrawn from the canister until they clear all obstructions (motion No. 1 on Fig. B-1). While roll-indexing is taking place, one half-column is swung over 180 degrees to bring it face to face with the other (motion No.2). Finally, the two half-columns are advanced toward each other and connected. The space requirement for this scheme is 37 meters long with a 10-meter lateral clearance for rotation of the half-column.

Description of Scheme No. 3, Fig. B-1

Scheme No. 3 is a modification of scheme No. 2, in which the terminal position of the completed column is rotated 90 degrees from the canister axis. In this case, both half-columns are placed face to face by means of 90 degree swings (motion No. 2) and connected in motion No. 3. The space requirement for this scheme is 27 meters x 20 meters.

Description of Scheme No. 4, Fig. B-1

Scheme No. 4 is a simplification of scheme No. 1, obtained by using the small ends to extract the half-columns from the canisters. This configuration halves the displacement of translation No. 3 without altering the space requirements, which remain at 37 meters. Special canister design is required.

Description of Scheme No. 5, Fig. B-1

Scheme No. 5 presents a method by which the number of translations can be reduced. In this case, column assembly can be performed in four motions plus roll-indexing. However, the space requirement is increased by 10 to 50 meters.

Description of Scheme No. 6, Fig. B-1

Scheme No. 6 presents one more step in the simplification of the translations required to connect the half-columns. The two canisters are placed face-to-face sufficiently to bring the two half-columns together while indexing them to perform the connection. A terminal lateral translation is then required to present the completed column to the platform assembly insertion mechanism or to the temporary storage canister. With this configuration, the space requirement increases to 53 meters.

Description of Scheme No. 7, Fig. B-1

Scheme No. 7 is a simplification of scheme No. 4 which provides a more compact arrangement. It follows closely the lines of scheme No. 4 but reduces the length requirements by about 7m. By similarity with schemes 1 and 4, the completed columns must be removed through the platen which supports the two canisters.

Description of Scheme No. 8, Fig. B-1

Scheme No. 8 is a further development of the ideas developed in schemes, 1, 4 and 7. In this scheme, the two column stacks are stowed in opposite directions in a common canister and the column connection is performed in the free space. This scheme can tolerate a temporary 10 m overhang so that its structural components can be limited to a length of 37 m. The operation consists in extracting by the small end the lower half-column, raising it in front of the other, performing roll-indexing and connection, then withdrawing the whole

column and transporting it to the manipulator capture position. By allowing a half-column length to overhang monentarily, the length requirement can be reduced to approximately 27 m.

Selection of a Half-Column Connector Scheme

If there is no problem of space availability, the selected scheme should require the least amount of manipulation. Scheme No. 6 is a strong candidate. However, the structural design of the appropriate assembly machine will undoubtedly present problems in meeting the stiffness requirements, owing to its larger size.

For the study of this discussion, the more compact schemes No. 7 and 8 are the most practical. The larger width of scheme 7 is a disadvantage and the transit of the completed column through the large cut-out in the platen which supports the canisters will present structural problems. Scheme No. 8, although somewhat simpler than No. 7, will require special attention to perform its translation without undue vibration. Selection of the best system should be performed on the basis of a more detailed study of these two solutions which are primarily intended for "in site" installation.

Working Head Design Concept

Half-column connection, using the NASA fitting, will be performed by a special device, namely the working head which is described in some detail in Section 5.3.

The following sequence of operations is applicable to schemes 2 and 3, which rotate the half-columns by 180 deg or 90 deg. The steps required to capture the two half-columns, extract them from the canister stacks, manipulate, connect, and finally release them, is shown on Fig. B-2.

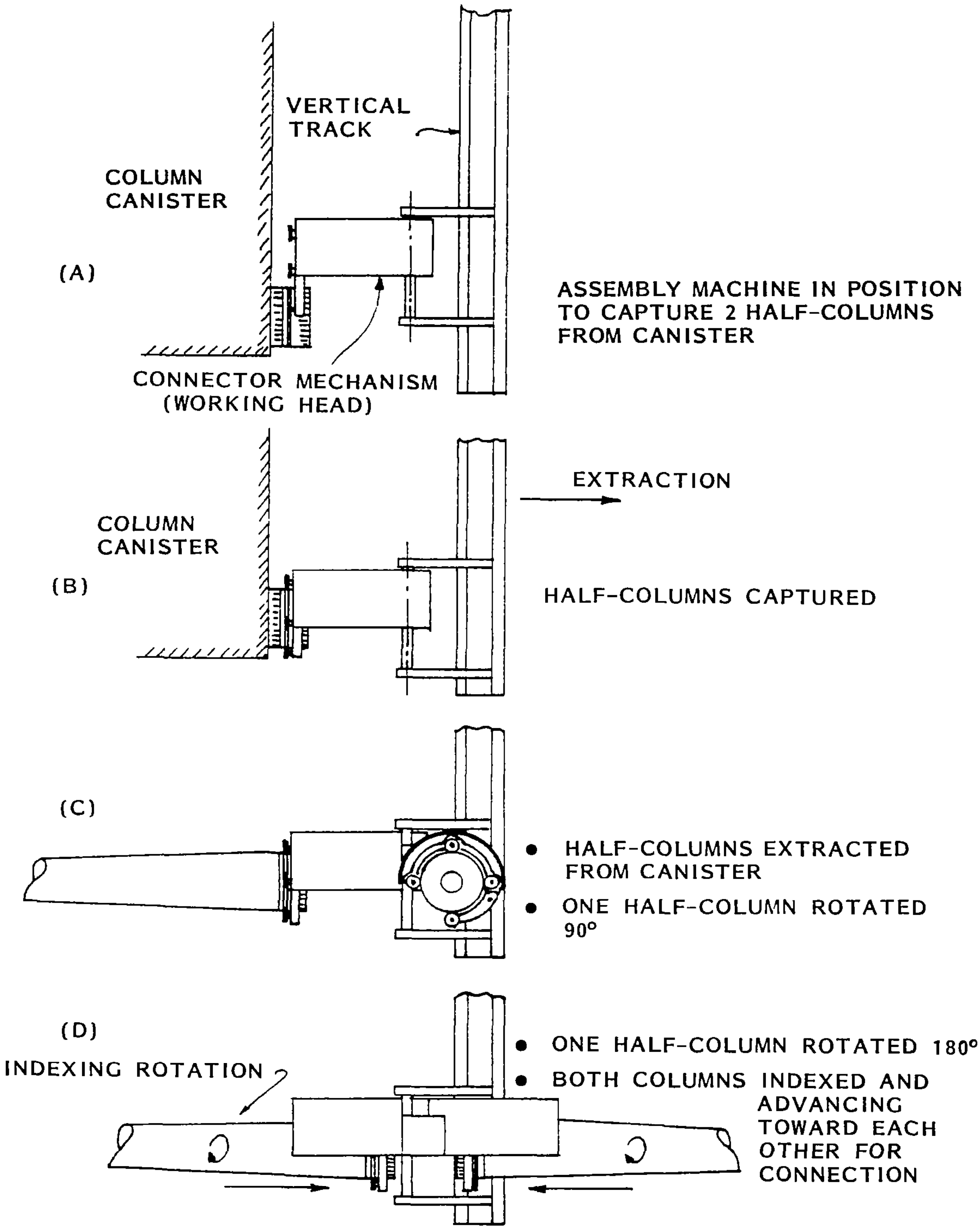


Figure B-2. Half-Column Assembly Sequence.

(Ref. Schemes 2 & 3 - Fig. B-1)

The general concept of this working head is applicable to other schemes as well, with appropriate modifications.

Figure B-2 shows the working head lowered into position just above the column end fitting. The working head has four rollers which match the shape of the end fitting capture groove. These rollers are aligned with the groove when the working head is set to capture.

On Fig. B-2, the working head is lowered down to the capture position with the capture arm closed. In this configuration, the working head firmly holds two half-columns, as shown on the scheme 2 assembly on Fig. B-1. The longitudinal track is then activated to move the head 10 meters toward the right, thereby disengaging the two half columns from the stack.

In the next operation, Fig. B-2, the working head rotates one of the half-columns by 180 degrees and locks itself in the proper alignment for connecting the two column end fittings.

Finally, on Fig. B-2, the working head is locked in the deployed position and the two half-columns are rotated to align the indexes. The connecting mechanisms drive the two half-columns toward each other until they are locked. This completes the assembly of the column, which is caught by other mechanisms and released from the working head. These mechanisms would handle the completed column by both small ends, either for direct installation on the platform being constructed, or for storage in a temporary canister.

A system of chain-driven tracks controls the motion of the working head along the three axis. The working head position can be set to extract columns from any cell of the canister. Since the canister presents the half-columns in pairs, it is possible to set up the stacks in a specified order in view of minimizing the tolerance scatter on the assembled column length.

The working head consists of two symmetric units designed to capture, manipulate, and release the half-columns. The detail design of these units must be adapted to meet the requirements of the column center-fitting configuration.

B-2 COLUMN HINGED CENTER JOINT

This section presents a hinged center joint design for application to folding columns for large space structures. In the concepts discussed previously, the 20 meter basic column is made up of two identical half-columns, which are stored in the fashion of plastic cups in the Space Shuttle. Assembly of these half-columns is accomplished by separate extraction from storage, rotation so that the castellated fittings match each other, then insertion and preloading to lock.

A folding structure can be made self-deployable and self-locking under the power of springs, while retaining the advantages of the plastic cup storage system. Using a self-locking four-bar linkage mechanism, a hinged center joint applicable to a folding column is presented here. Deployment of these columns can be accomplished automatically with the help of a relatively simple machine which can be adapted directly to the tracked assembler Section A2, where it may be used either to feed the column distributors or be adapted to replace it altogether. Its application to the gimballed parallelogram assembler is also possible, with appropriate modifications to meet the conditions peculiar to each of the loading points.

Description of Column Center Hinge

The hinge fitting mechanism and its kinematics are shown on Fig. B-3. The system consists of four major components: the column large fitting ends which form the spring loaded center hinge, and the two pairs of linkages. One link is adjustable in length in order to provide preload control in the deployed position. The other link is rigid and powered by a torsion spring. Locking

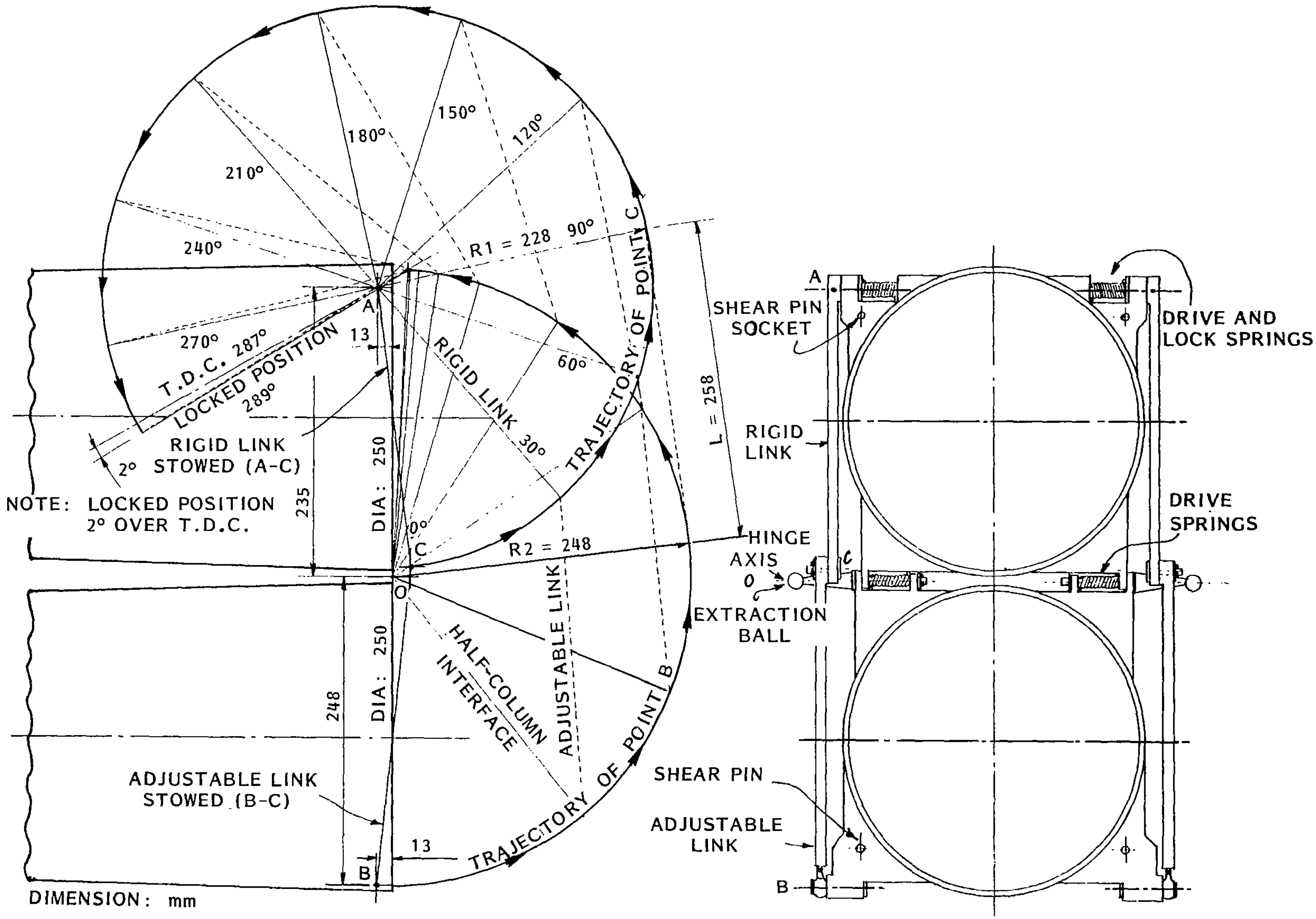


Figure B-3. Hinge Fitting Mechanism and Kinematics.

is obtained when the rigid link goes over t.d.c. A two degree overshoot is allowed to make the mechanism irreversible without significant reduction of the preload.

The kinematics of the system is shown in detail in Fig. B-3, where the upper half-column is held fixed while the lower half is allowed to rotate about the hinge point O. The relative angular displacements of points B and C are clearly shown. The mechanical advantage of the spring at point A tends to go to infinity at t.d.c.

Column Configuration During Deployment

Figure B-4 shows the configuration of the column at a point about midway between open and closed. Note that the fittings include a set of two shear pins which fit into appropriate sockets in the closed position. These shear pins eliminate a degree of freedom which could be detrimental to the rigidity of the deployed column.

Each hinge fitting has a conical skirt to the taper of the composite column which is bonded to it.

Since the half-column configuration remains essentially similar to that of the previous single plastic cup stacking scheme, the capability to be stacked double-cup fashion is preserved. In fact, the compactness of the stacking may be improved over that of the single scheme.

Column Configuration After Deployment

Figure B-5 shows the hinge in the deployed configuration, with the four-bar linkage in the locked position and the shear pins set in their sockets. A double system of stops in shown to ensure that the linkages will not overshoot t.d.c. by more than the specified two degrees. However, since the moment arms of these stops are necessarily small, a positive locking system should be added. Although experience with self-locking four-bar linkages has shown that

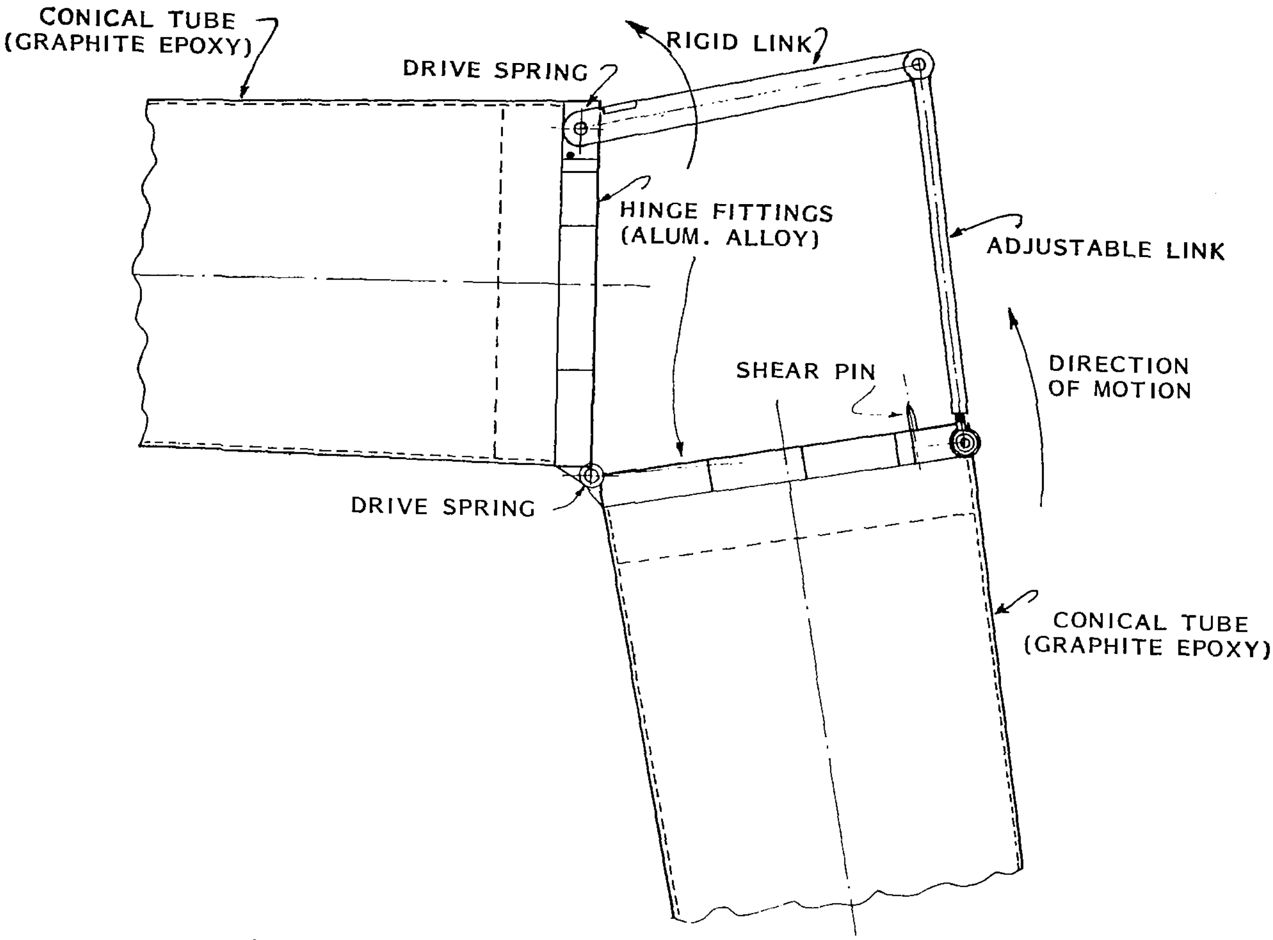


Figure B-4. Self-Deployable Column, Partial Deployment.

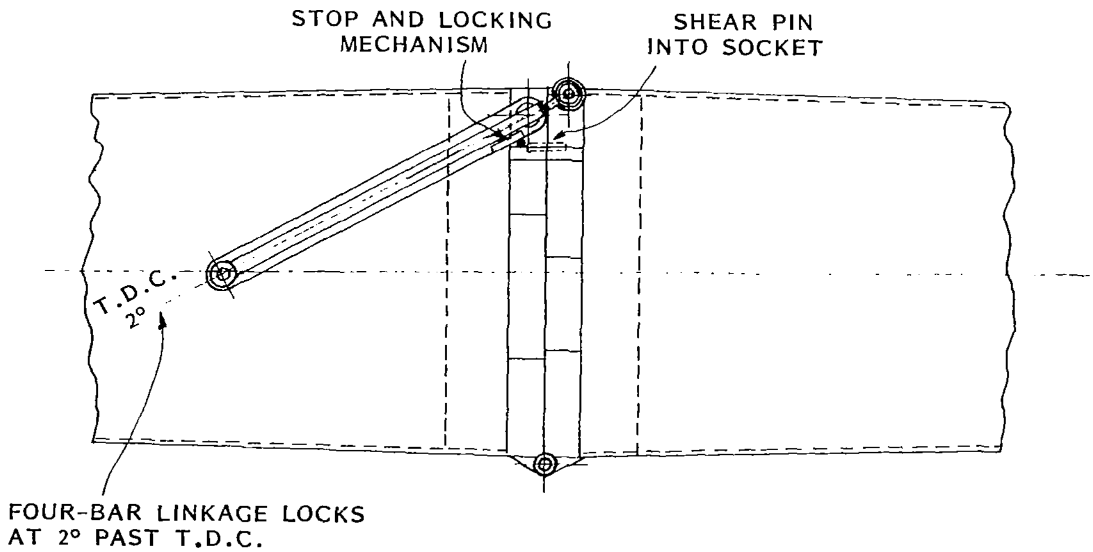


Figure B-5. Self-Deployable Column, Fully Deployed.

they are normally irreversible, there is a possibility of accidental disturbance. For example, they could be kicked open during EVA. Therefore, the added safety of a positive lock is an insurance against such an eventuality.

The locked position of the four-bar linkage was set in this design to coincide with one diameter of the column. This position was selected to minimize the clearance between linkage and tube, and reduce the chances of getting EVA gear entangled in the mechanism.

Deployment Velocity

Under the spring torques, the deployment would be continuously accelerated, resulting in a large lockup angular velocity and correspondingly high lockup loads. To prevent detrimental lockup loads which would be generated under these conditions, the system must be provided with damping to control the velocity. A simple solution to this problem consists in fitting small hydraulic shear dampers or their mechanical equivalent at the hinges. Since these devices are quite conventional, no particular difficulties should be encountered in integrating them into the design. Velocity within a specified range can then be otained by appropriate sizing of springs and dampers. It is estimated that a deployment time of 20 to 30 seconds would be satisfactory.

Material And Parts Manufacturing

The most logical material for these hinges is an aluminum alloy of appropriate characteristics. However, it may be possible to consider graphite/epoxy as an alternate for the two hinge components, leaving the linkage to be made of metal.

As shown on Figs. B-3, B-4 and B-5, the layout considers fabrication by machining. This is appropriate for a demonstration model, but large quantity production would require special consideration.

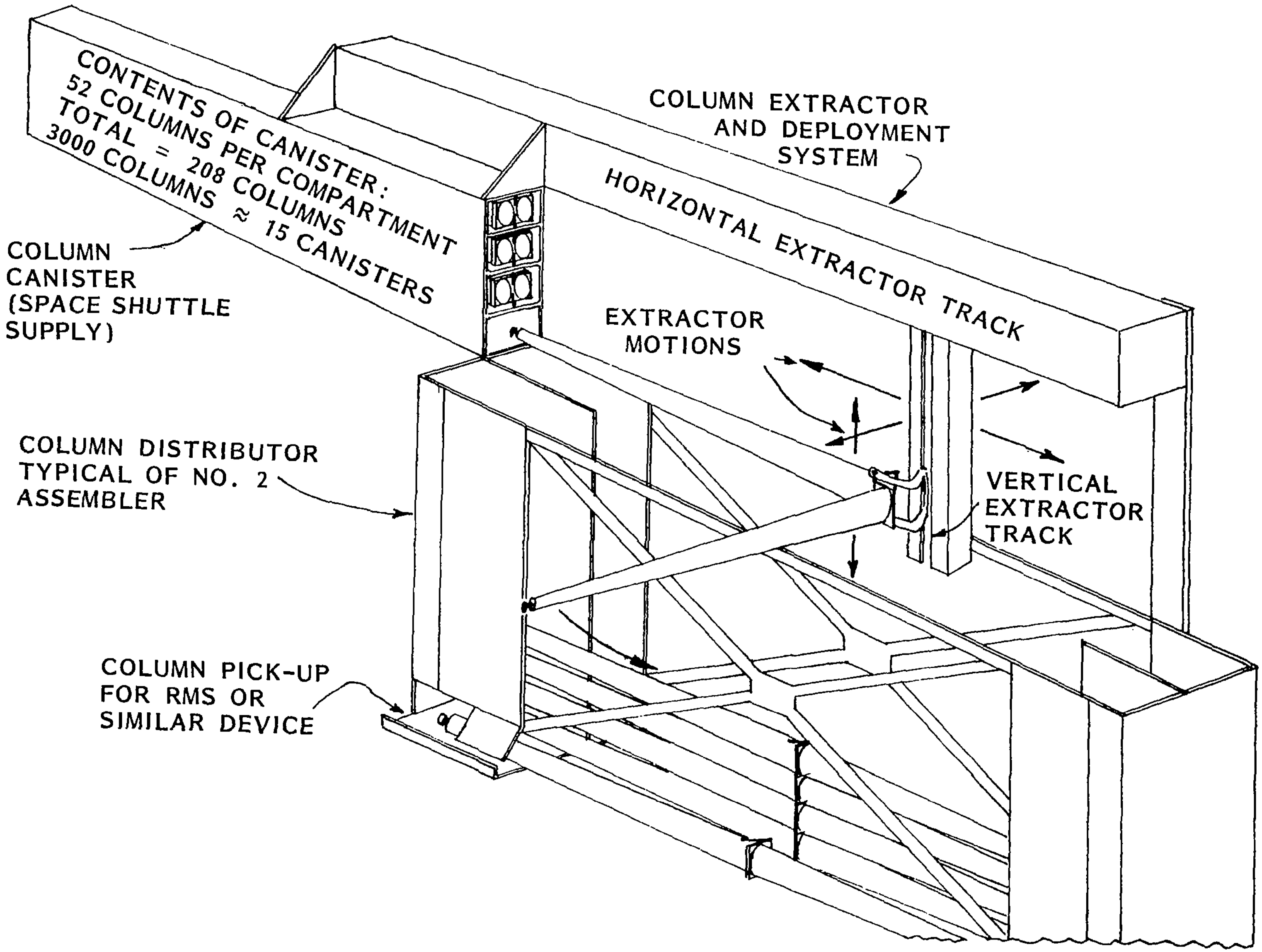


Figure B-6. Stowage, Deployment, and Loading of Columns.

B-3 OFF-SITE HALF-COLUMN ASSEMBLY

The half-column assembly machine described in this Section was conceived as an adjunct to the tracked platform assembler of Appendix A which has an off-site option of column assembly.

In order to take full advantage of the self-deploying feature of the hinged columns, the concept of an appropriate deployment system was devised. This machine, shown on Fig. B-6, is based on a track mechanism similar to that considered for the tracked platform assembler of Appendix A. However, the general concept is not restricted to the use of folding columns. It can be adapted to the separate half-column system by using the working head described on Fig. B-2.

It should be noted that the use of this procedure greatly simplifies the design of the column canisters and makes it easily adaptable to presenting matched pairs of half-columns for assembly, providing closer tolerances after connection. This system, unfortunately, is not easily amenable to "in-situ" installation.

This machine consists of two chain driven tracks. The horizontal track, shown on Fig. B-6, is the column extractor; the vertical track aligns the extractor claw with a selected compartment of the column canister or magazine. The column canister must be fitted with a mechanism which advances the stack one column at a time to the capture position. A motor driven chain-track system seems appropriate, since a spring-loaded mechanism with a 7 meter stroke appears impractical.

The column deployment procedure is as follows:

a. A column canister is attached to the machine and its safety lock released so that every column stack is allowed to move out to place the first column in each compartment with its hinge system in the capture area.

b. The vertical extractor track is adjusted to align it with one of the chambers of the canister.

c. The horizontal extractor track is activated toward the left (Fig. B-6) to bring the extractor claw in position over the extraction balls, which are fitted on each end of the column hinge axis. These balls are shown on Fig. B-3.

d. The extractor claws are then closed and locked over the extraction balls, thus capturing the column.

e. The horizontal extractor track is moved toward the right (Fig. B-6) to pull the column free from the canister stack.

f. Once the column small ends emerge and are free from the stack, deployment starts automatically under the spring torque.

g. At the end of deployment, an option is available to set up a mechanism for checking the four-bar linkage position and ensuring positive lockup.

h. The vertical track is activated to lower the deployed column and bring it within grasp of the transport mechanism. This transport mechanism may be a column distributor, as shown on Fig. B-6, or the robotic arms of the tracked assembler in Appendix A.

i. The claw is opened to release the column as soon as the transport mechanism has captured it.

j. Both tracks are activated to return to the start of the cycle and capture another column.

Note that the extractor claw and column extraction balls must be designed to prevent rotation of one half-column, as shown on Fig. B-6. This design must

also be capable of withstanding the loading conditions provided by the column deployment stop transient and maintain the orientation of the column within specified tolerances. However, a system of guides can be devised to assist this mechanism in maintaining the desired orientation.

Construction of The Column Deployment Machine

The concept of the structural and mechanical design of the column deployment machine follows the lines of the structure selected for the tracked assembler. The track mechanism can use the same collapsible structural elements as shown on Fig. A-17 and A-19, and described in Appendix A with a simplified rail system.

The column canisters must be fitted with toggle latches located to match hard points on the machine and permit simple attachment and removal by astronauts in EVA.

Conclusion

This conceptual study shows that folding columns can be designed without particular difficulties and offer attractive possiblities to simplify the assembly of large space structures.

The cost of manufacturing this more complex mechanism might be greater than the snap-on type. However, the advantages it does offer from the standpoint of easier handling in orbit and greater reliability may offset the greater manufacturing costs.

APPENDIX C

HIGH STORAGE EFFICIENCY COLUMN ASSEMBLY CONCEPT

This appendix presents a study of the mechanisms required for the operation of the half-column assembler of scheme No. 7 in Appendix B of the main report. This concept, which is a modification of that presented in Ref 2 merits further investigation because of its high storage efficiency.

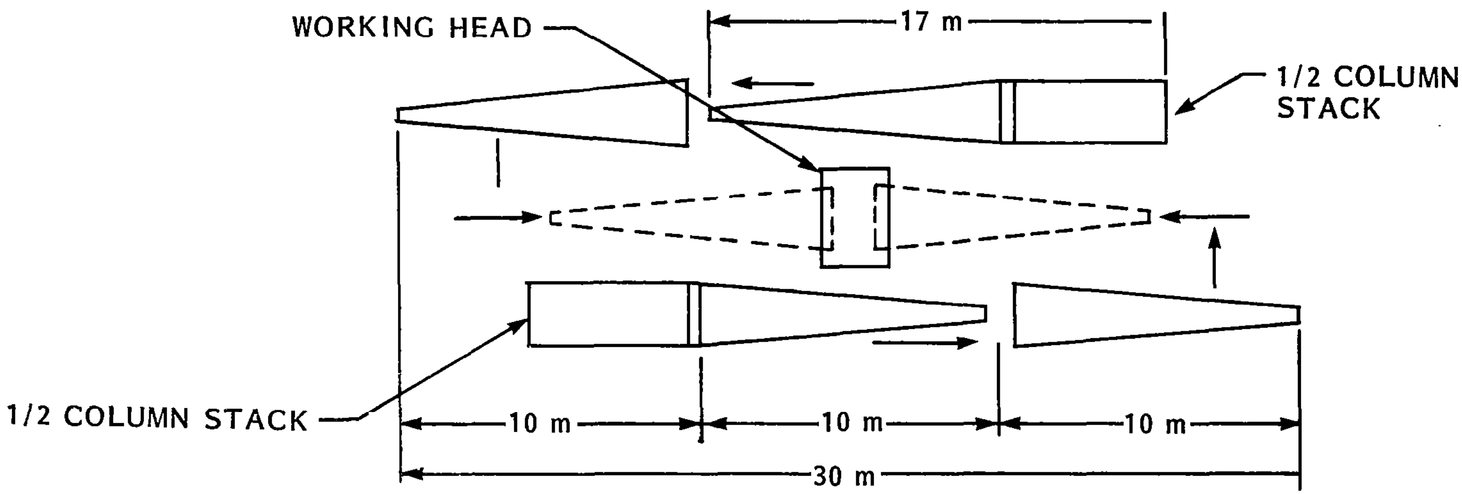
The basic scheme is shown schematically on Fig. C-1 and C-2.

It can be seen that the motion of the two half-columns is symmetric such that the same mechanism can be used to perform either translation. In addition to translation, the two half-columns are indexed by rotating them to match appropriate markings on the large end fittings. A working head similar to that which is described in Section 5.3 can be used to perform this operation. The location of this working head is shown on Fig. C-1 and C-2 at the point where the two half-columns will meet. The total motion to be imparted to the half-columns consists of 3 linear translations: extraction and withdrawal from stack, lateral transfer, advance to capture by working head, indexing and finally insertion.

The first three parts of the motion are simple linear translations which can be easily achieved by a system of tracks with linear ball-bearing runners as shown on Fig. C-3. The short track, which provides lateral transfer, is mounted on a carriage which runs on the platen tracks. The half-column carrier is mounted on a secondary carriage which must perform several functions as described below.

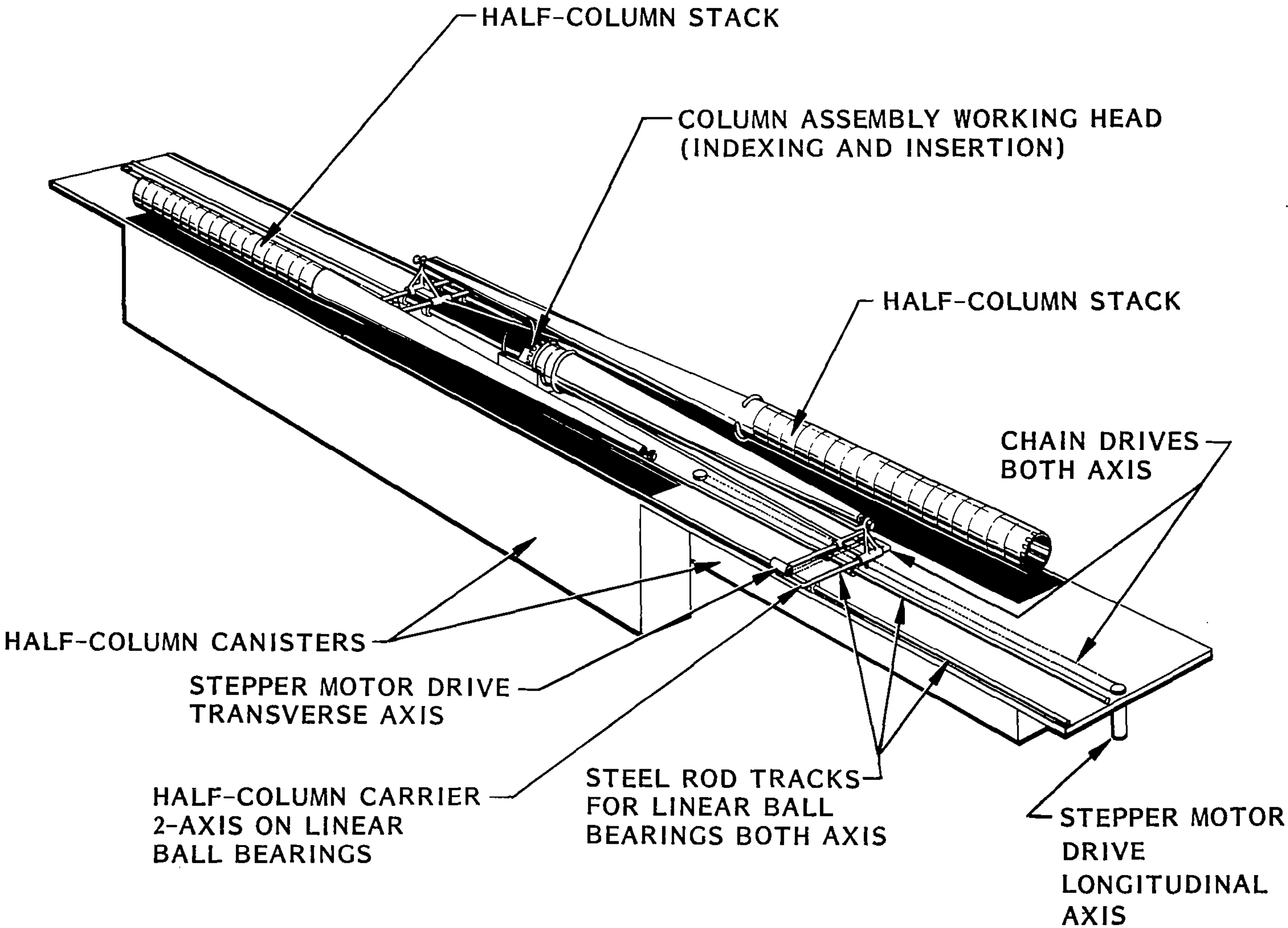
Secondary Carrier

As a first-step in this conceptual study, it is assumed that a single lateral transfer track will provide satisfactory rigidity by means of a system of



SCHEME 7

Figure C-1. Schematics of Half-Column Assembly.



NOTE: HALF-COLUMN STACK ADVANCE FROM CANISTERS AND HALF-COLUMN ADVANCE TO EXTRACTION SYSTEM NOT SHOWN FOR CLARITY.

Figure C-2. General Arrangement of Column Assembly Scheme.

locks. However, if the stiffness criteria cannot be met in this manner, a double track system, as shown on Fig. C-4, can be developed with some penalty in mechanical complication and weight.

The secondary carrier captures the half-column by both ends and holds it securely during extraction, withdrawal and transfer. The half-column is held at the large end by a clamp which provides only radial restraint. At the small end, another clamp provides both axial and radial restraint.

The half-column stack, as it emerges from the canister, is held by a holding device which locates it above the platen in a position accessible to the secondary carrier mechanism. Then two possible mechanisms can be used:

1. The half-column stack remains stationary and the carrier advances one step further to capture each successive half-column.

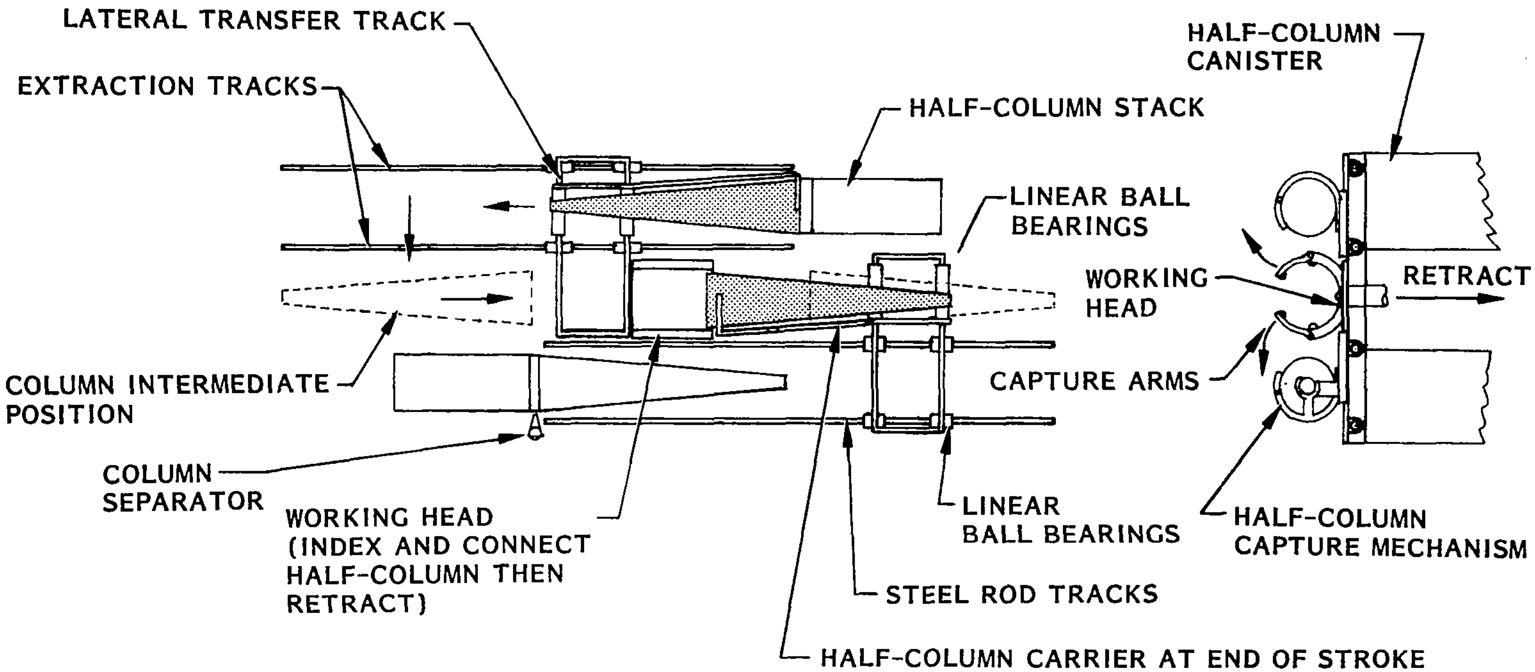
2. The half-column stack is moved one step at a time toward the carrier which captures the half-columns always at the same location.

A detailed trade-off study is required to determine which of these two systems is most advantageous.

With the nested stacking system provisions must be made to overcome significant static friction forces in the event that one half-column sticks inside of another. It may be possible to provide a separator between columns such as mylar or teflon film. At this stage of this conceptual investigation a mechanism is included to overcome the static forces.

This mechanism should be combined with the stack advance and holding mechanism. Its location is shown schematically on Fig. C-3.

After the carriers have transported the two half-columns to the working head capture position, the large end clamps are moved away from the working head



NOTE:
- HALF-COLUMN CARRIERS ARE OPERATED BY CHAIN DRIVES ALONG BOTH AXES
- STEPPER MOTORS PROVIDE POSITION CONTROL
- NOT SHOWN – COLUMN STACKS ADVANCE MECHANISMS

Figure C-3. Schematic of Column Extractor.

capture areas. This can be accomplished by mounting the clamps on a short spring loaded track such that the clamp is held back to clear the working head path by a stop mounted on the platen.

Working Head

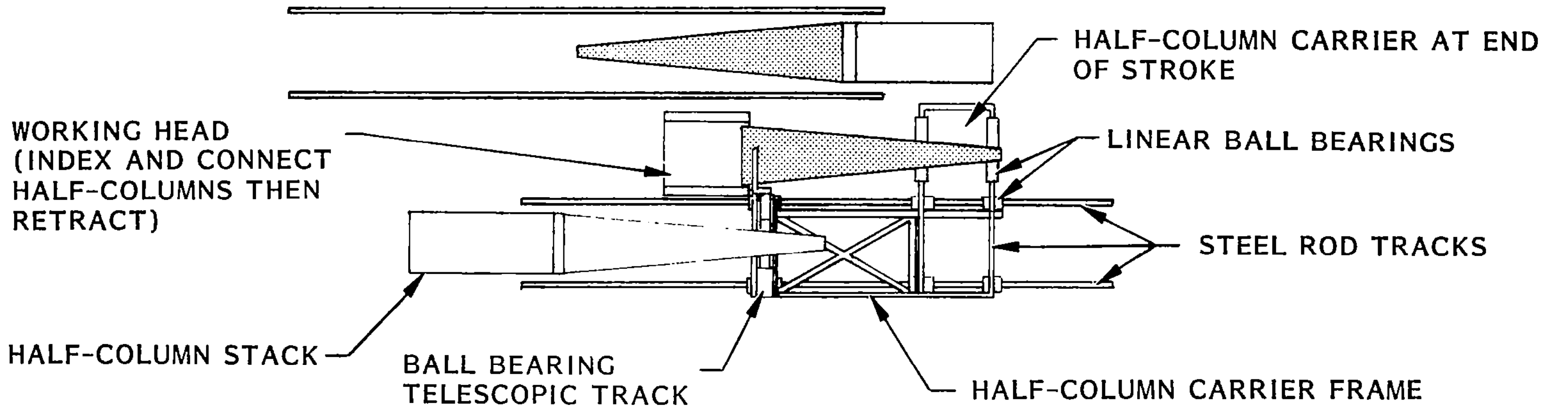
The working head is essentially the device shown in Section 5.3 of the report and performs the same function. The only significant difference is in its mounting which must be adapted to this particular application. At rest, the working head must be withdrawn toward the platen in order to clear the path of the two half-columns. Once the two half-columns are properly located, the head is advanced to capture them and perform its indexing and connecting functions. Then it disconnects itself from the column and returns to its rest position.

Final Function: End of Cycle

Once the column is completed, the carrier clamps must be activated to release it to the assembler manipulators.

Utilities Installation

The installation of electric cables and fluid lines on the columns has been examined in some details but the conclusion does not favor this half-column assembly scheme because of significant complexity and the need for separate canisters and handling equipment. It is for this reason that the half-column assembly scheme No. 8 was selected for application to the gimballed parallelogram platform assembler.



NOTE:
- HALF-COLUMN CARRIERS ARE OPERATED BY CHAIN DRIVES ALONG BOTH AXES
- STEPPER MOTORS PROVIDE POSITION CONTROL
- NOT SHOWN – HALF-COLUMN STACKS ADVANCE MECHANISMS

Figure C-4. Schematic of Column Extractor with Double Lateral Track.

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15. Supplementary Notes

Langley Technical Monitor: Harold G. Bush
Final Report

16. Abstract

This study examined the technology associated with the on-orbit assembly of tetrahedral truss platforms erected of graphite epoxy tapered columns. Associated with the assembly process is the design and fabrication of nine-member node joints. Two such joints, demonstrating somewhat different technology, were designed and fabricated.

Two methods of automatic assembly using the node designs were investigated, and the time of assembly of tetrahedral truss structures up to 1 km^2 in size was established. The effect of column and node joint packaging on the Space Shuttle cargo bay is examined. A brief discussion is included of operating cost considerations and the selection of energy sources.

Consideration was given to the design of assembly machines from 5 m to 20 m. The smaller machines, mounted on the Space Shuttle, would be deployable and restowable. They would provide a means of demonstrating the capabilities of the concept and of erecting small specialized platforms on relatively short notice.

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